HATEM A. FARAG EMBARESH

ANALYSIS AND SIMULATION OF Z-SOURCE BASED AC-AC CONVERTER

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A THESIS SUBMITTED TO THE GRADUATE SCHOOL OF APPLIED SCIENCES OF NEAR EAST UNIVERSITY

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In Partial Fulfilment of the Requirements for the Degree of Master of Science in Electrical and Electronic Engineering

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Approval of Director of Graduate School of Applied Sciences

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We certify this thesis is satisfactory for the award of the degree of Master of Science in Electrical and Electronic Engineering

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To my parents…

ABSTRACT

This thesis present analysis and simulation of a single-phase AC-AC converter based on impedance source (ZS) and high frequency transformer (HFT) isolation. The converter can work in both buck and boost modes and hence is a buck-boost. This converter maintains the important features of the non-isolated Z-Source AC-AC converters, which include; high voltage gain, wide range of step-up and step-down output-voltage, and improved reliability. Additionally, for electrical isolation and safety high frequency transformer (HFT) is used in the circuit, and therefore there is no need for external bulky line frequency transformer, for applications such as dynamic voltage restorers (DVRs).

The converter circuit is obtained by modifying the non-isolated ZS AC-AC converter, by adding a single bidirectional switch, and replacing two inductors in the non-isolated converter with the HFT, which means one magnetic core is reduced. Detailed analysis of the converter in steady state for HFT turn ratio $n = 1$ is performed by using a suitable key waveforms and equivalent circuits. The converter operates in both boost and buck mode; it operates in a boost mode when the duty ratio is $0 < D < 0.5$ and buck mode for $0.66 < D < 1$. In both cases the relevant relationships between various components voltages and currents have been established.

Finally, for performance evaluation, a simulation is conducted by using PSCAD / EMTDC-V4.2 software. The theoretical and simulation results indicated that the converter can step-up and step-down the voltage and produces a good result.

***Keywords*:** AC-AC converter; Z-source converter; High-frequency transformer (HFT);Isolation; buck-boost; dynamic voltage restorers (DVR); PSCAD/EMTDC package

ÖZET

Bu bitirme tezi, tek faz alternatif akım-alternatif akım (AC-AC) çevirgecinin, empedans kaynak (ZS) ve yüksek frekans transformatör (HFT) izolasyonu baz alınarak analiz ve simülasyonunu sunmaktadır. Çevirgeç, hem sıçrama hem de yükseltme modlarında çalışabildiği için sıçrama-yükseltmedir. Bu çevirgeç; yüksek gerilim kazanımı, çeşitli sayıda artırıcı ve azaltıcı çıkış voltajı, ve geliştirilmiş güvenirlik içeren izole olmayan alternatif akım – alternatif akım (AC-AC) çevirgeçlerinin önemli özelliklerini devam ettirmektedir. Bunaek olarak, çevrimde, elektrik izolasyonu ve güvenliği için, yüksek frekans transformatör (HFT) kullanılmakta ve dolayısıyla, dinamik gerilim restore edenler (DVR'ler) için, dışsal kocaman hat gerilim transformatörüne ihtiyaç olmamaktadır.

Çevirgeç devresi; bir adet mıknatıs çekirdeği azaltılması anlamına gelen, izole olmayan ZS alternatif akım – alternatif akım çevirgeci modifiye etmek, iki yönlü tek anahtar ilave etmek ve izole olmayan çevirgeçteki iki indüktörü HFT ile değiştirmek suretiyle, elde edilmiştir. Uygun bir anahtar dalga şekilleri ve muadil çevrimler kullanılarak durağan durumdaki çevirgecin HFT'ye döndürme rasyosu n=1 için ayrıntılı analiz yapılmıştır. Çevirgeç, hem yükseltme hem de sıçrama modunda çalışmaktadır; çalışma doluluğu oranı $0 < D < 0.5$ olduğu zaman yükseltme modunda, ve $0.66 < D < 1$ olduğu zaman da sıçrama modunda çalışmaktadır. Her iki halde de, çeşitli bileşenler, gerilimler ve akımlar arasındaki ilgili ilişkiler kurulmuş bulunmaktadır.

En sonunda, performans değerlendirilmesi için, PSCAD/EMTDC-V4.2 yazılım programı kulanılarak bir simülasyon modeli icra edilmiştir. Kuramsal ve simülasyon sonuçları, çevirgecin gerilimi artırabileceğini ve düşürebileceğini göstermiş ve çevirgeç iyi bir sonuç üretmiştir.

***Anahtar Kelimeler*:** Alternatif akım – Alternatif akım çevirgeci; Z-kaynak çevirgeç; Yüksek frekans transformatör (HFT); İzolasyon, sıçrama–yükseltme; dinamik gerilim restore edenler (DVR); PSCAD/EMTDC paket programı

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AC: Alternating Current

DC: Direct Current

ZS: Impedance Source

HFT: High Frequency Transformer electromagnetic interference

DVR: Dynamic Voltage Restorer

ZSI: Z-Source Inverter

qZS: Quasi-Z-Source

EMI: Electromagnetic Interference

PSCAD: Power System Computer Aided Design

CHAPTER 1

INTRODUCTION

1.1 Introduction

The salient features of direct PWM controlled ac-ac converter have made it more suitable for applications that requires regulating voltage solely. Among the advantages of these converters are; low cost, single-stage conversion, small size, high efficiency, lower current-harmonics as well as high power factor (Ahmed, Cha, Aleem, Khan, & Kim, 2015). Many research have been carried out to investigate the circuit design, analysis and control approaches for PWM based PWM ac-ac converter (Chen & Liu, 2006). The buck-boost type of these converters are discussed in (Giri, Brian, & Ashok, 1996) and (Sarnago, Lucia, Mediano, & Burdio, 2014). In (Jong-Hyun, Byung-Duk, & Bong-Hwan, 1992) single-phase version of this converter is also suggested in order to alleviate the limited voltage gain. The single-phase Cuk ac-ac which is also a type of the converter introduced in (Fang Zheng, Lihua, & Fan, 2003; Hoyo, Alcalá, & Calleja, 2004) is able to offer voltage step up and down similar to buck-boost. They also offered the benefit of exhibiting a constant input-current and output-current. Another unique set of single phase converters with multiple cells are introduced, these set of ac-ac converters increase the quality of voltage output and decreases voltage stress exerted on the switch (Stala et al., 2009; Wilkinson, du Mouton, & Meynard, 2006). The aforementioned direct converters are often used as dynamic-voltage restorers (DVRs) (Jothibasu & Mishra, 2015; Lee, Habetler, Harley, Rostron, & Keister, 2004), in order to fix static volt-ampere reactive (VAR) and also fix voltage swell and sags in power systems (Ye, 1999).

Peng introduced a unique converter topology using an LC network named Z-network, to serve as interface between the DC source and the converter. This network solved consists of symmetrical passive components connected in X-shape. The new source differs from the conventional sources and is popularly known as Z-source (Fang Zheng Peng, 2003a). Z-source technique has solved many of the limitations of conventional converters and exhibit unique features for instance, it provides a high output-voltage, and can handle a current shoot-through problem. Consequently, Z-source strategy has been applied in DC-DC converters to achieve broader output voltage. Peng has presented a number of Z-source circuits (Ge, Lei, Qian, & Peng, 2012; J. C. Rosas-Caro, Peng, Cha, & Rogers, 2009) with their associated control strategies (Shen et al., 2006), (Y. Li, Jiang, Cintron-Rivera, & Peng, 2013).

A quasi-impedance network (qZS) based ac-ac converters can also provide all the advantages and beneficial characteristics of Z-network based ac ac converters (Minh-Khai, Young-Gook, & Young-Cheol, 2010). Additionally, it offers less voltage stresses on the capacitors, mutual space amid input and output and constant input current. An improved quasi-impedance network (qZS) based ac-ac converters with single phase is proposed. This topology has less amount of passive elements in comparison with both quasi-impedance network (qZS) based ac-ac converter and Z-network converter type (M. K. Nguyen, Lim, & Kim, 2012). The approach of soft commutation is adopted in order to remove voltage spikes of switches as presented in (M. K. Nguyen et al., 2012; Tang, Zhang, & Xie, 2007). Further modification is made in gamma Z-network ac ac converter which is on the basis of coupled inductor (Banaei, Alizadeh, Jahanyari, & Seifi Najmi, 2016). This topology is based on coupled inductor, and it is able to regulate voltage gain through changing the coupled inductor turns ratio as well as the converter's duty ratio simultaneously.

1.2 Problem Statement

Despite the advantages and special characteristics exhibited by Z-network based single-phase ac-ac non-isolated converters discussed in the literature, when used as dynamic voltage restorers (DVRs) for utility voltage swells and sags compensation (Kaykhosravi, Azli, Khosravi, & Najafi, 2012), an isolation between utility grid side and the output side (electronic load) is provided via an externally bulk line frequency transformer. Aforesaid frequency transformers have saturation problem and start-up inrush current, additionally, they are heavy and bulky resulting in increased cost and losses (B. H. Li, Choi, & Vilathgamuwa, 2002; Newman, Holmes, Nielsen, & Blaabjerg, 2005; Wang, Tang, Yu, & Zheng, 2006). Moreover, voltage drop is resulted due to high impedance of this low-frequency transformers, and the voltage harmonics becomes serious alongside non-linear loads (Newman et al., 2005). In order to alleviate above shortcomings, HFT isolated (HFTI) Z-network based ac-ac converters are introduced (Ahmed, Cha, Khan, & Kim, 2016). Such converter topology exterminates the necessity of externally line frequency transformer if adopted as DVR. Nevertheless, this converter uses additional bidirectional switch and extra passive components which increase their losses, volume, and cost.

In this thesis, the converter under study is introduced to subdue the above shortcomings of classical Z-source based ac-ac converters (X. P. Fang, Qian, & Peng, 2005; Minh-Khai et al., 2010; M. K. Nguyen et al., 2012; Tang et al., 2007) as well as classical HFTI Z-source based ac-ac converter introduced in (Ahmed et al., 2016). It keeps the overall features of classical Z-source based ac-ac converters. It has HFT isolation and less passive component-count, HFT is incorporated for safety and electrical isolation. This is implying that an external line frequency transformer that is huge and expensive can be conserved for various uses like DVRs.

1.3 Objectives

In this thesis, analysis and simulation of Z-source based ac-ac converter is presented. In addition, possible application of this converter as DVRs is also analysed. This will be accomplished through the following objectives:

i. Converter circuit description
ii. Theoretical analysis of the converter circuit in both boost and buck operation modes with associated waveforms and equivalent circuits
iii. Components parameter selections
iv. Application of the new converter as DVRs
v. Simulation of the converter using PSCAD software

1.4 Significance and Limitations

The high frequency transformer (HFT) isolated Z-source based ac-ac converter, under discussion acquire all the salient characteristics of their non-isolated types, which includes; broad extent of buck-boost output voltage, improved reliability and ability to handle the harmonic and in-rush currents. Additionally, for electrical isolation and safety HFT is incorporated with HFT’s, and hence eliminate the huge line frequency transformer, for use in various aspects like dynamic voltage restorers (DVRs), etc.

The converter make use of a single extra bidirectional switch when related to their regular non-isolated equals, and possess similar or fewer inactive components requirement, by substituting two inductors in the non-isolated converter with HFT, which means one magnetic core is reduced, when you relate it to the isolated Z-source converters (Minh-Khai et al., 2010), thereby, reducing the losses, volume and cost.

This thesis work is limited to theoretical analysis and software simulation. For the analysis all the components are considered to be ideal for simplicity. Only one application of the converter is presented i.e. their use as dynamic voltage restorers (DVRs).

1.5 Thesis Organization

The thesis is arranged in four chapters. In chapter one an introduction and background of the thesis; including problem statement, objectives, significance of the work are presented. Literature review on Z-source inverters is given in chapter two. Power circuit description, its operation, components parameter selection, and simulation results are presented in chapter three. Chapter four present conclusion of the thesis work and discusses some recommendations for future work.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The advantages and functions of power electronics converters cannot be over exaggerated. The need for power electronics converters is exponentially increasing, as the demand for equipment and systems that uses power electronics converters is growing rapidly. Power electronics converters are typically used as interface to conditioned a given power source to make it suitable for the load. Power electronics converters are classified based on the nature of input/output voltage they operate on into; ac-ac, ac-dc, dc-ac, and dc-dc.

In this regard ac-ac converters are used in applications where an ac voltage source is required to be change from one magnitude and frequency condition to another form suitable for an ac load. These converters are often needed for speed control in machine, variable voltage applications. Since there are variety of ac loads such as single-phase, three-phase, therefore different converter topologies are used.

In ac/ac conversion where variable output-voltage with variable frequency is required, voltage source inverter combined with dc-link and front-end rectifier is often used. On the other hand, for applications where voltage regulation is the only requirement, direct pulse-width-modulation (PWM) ac/ac converters are the obvious choice. The salient features of direct PWM controlled ac-ac converter have made it more suitable for applications that requires regulating voltage solely. Among the advantages of these converters are; low cost, single-stage conversion, small size, high efficiency, lower current-harmonics as well as high power factor (Ahmed et al., 2015).

Other applications of AC/AC converters, include isolation, filtering and voltage conditioning to mention few (Fang Zheng et al., 2003). The performance and efficiency of the PWM controlled ac-ac converter can be significantly improved by using of self-commutation strategies in the switches with PWM control can significantly improve the performance of ac–ac converters. This has been proposed in many research publications

(Aeloiza, Enjeti, L. A. Moran, & Pitel, 2003; Fang Zheng et al., 2003; Lin, Yang, & Wei, 2003; Vinnikov, Chub, & Liivik, 2015; Xue, Chang, & Song, 2004), in which different types of ac/ac converters are discussed. In many cases simulation and protypes are used to illustrate the performance of these converters in solving problems like voltage swell, sag, and load fluctuations. where different ac-ac converters were proposed. The Z-source inverter is a special topology (Fang Z Peng, 2004; Fang Zheng Peng, 2003b) that solves the theoretical and conceptual limitations of the conventional current source and voltage source convers.

This chapter presents and discuss the different types of ac/ac converter topologies in the literature, including the three-phase, single-phase, dc-link and matrix ac-ac converters. Discussed here also are the isolated and non-isolated converters. The converter topologies that integrate Z-source network and traditional ac-ac converters to form Z-source based ac-ac converters are also discussed. Finally, the application of the converter as a DVR is also explored. For the purpose of this literature review, the converters are classified into classical and Z-source based ac-ac converters as depicted in Figure 2.1.

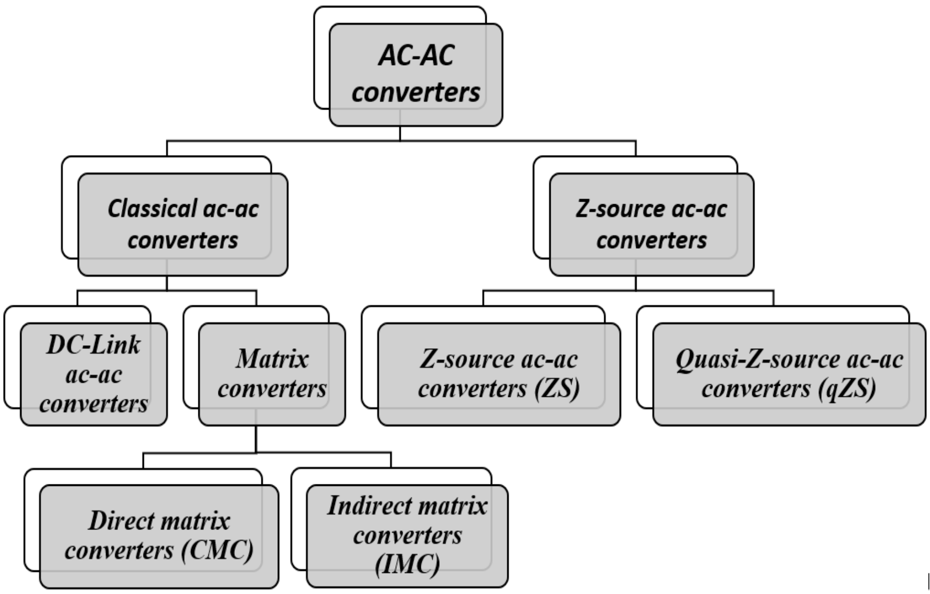


Figure 2.1: Classification of ac-ac converters reviewed

2.2 Classical AC-AC Converters

The AC to AC converters can be classified into different types including single-phase, three-phased, DC link, Matrix converters and hybrid matrix converters

2.2.1 DC-Link AC-AC Converters

DC-link ac-ac converters are formed by combining pulse-width-modulated (PWM) rectifier dc link and inverter dc link. Energy storage component (capacitor or inductor) is used to suppressed the dc quantity. Because of the energy storing element in the dc link, the two converter circuits are separated which makes the sizing for energy storing component easy. Nevertheless, the additional dc link increases the size and volume of the converter, and reduces the operation lifetime if the dc link is formed with electrolytic capacitor.

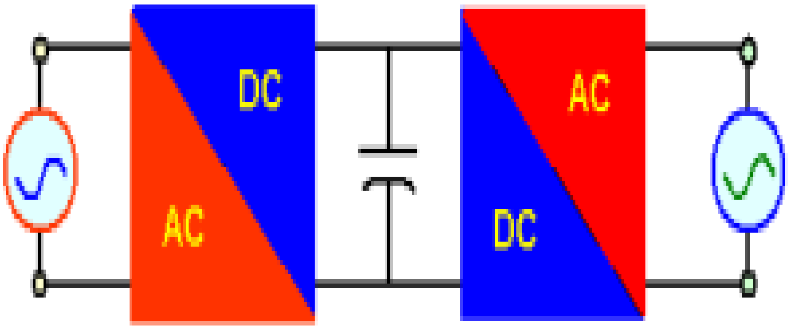


Figure 2.2: DC-link AC-AC Converters (Jothibasu & Mishra, 2015)

The dc link can be considered in three categories, voltage-dc-link, current-dc-link and voltage-current-dc-link. A voltage-dc-link converter is presented in (Takahashi & Itoh, 1990),Figure 2.3, shows the output inverter side for this topology, it consist of three legs which act as switches to connect the output to the dc-link. is made up of three bridge legs. The operation is limited to one free-wheeling state in every single pulse, which makes it necessary to always have one leg connected to p or n, and therefore switching losses are avoided in that bridge-leg.

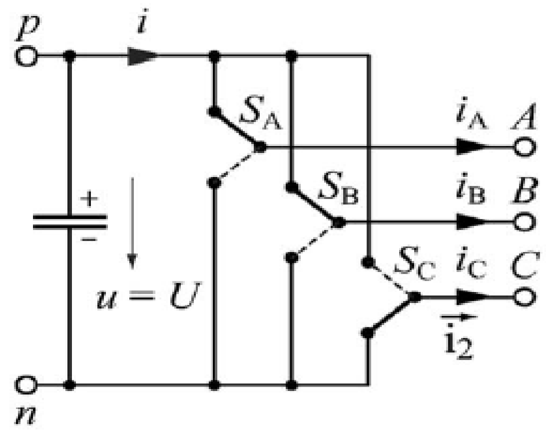


Figure 2.3: Voltage dc-link converters (Takahashi & Itoh, 1990)

Figure 2.4 shows the input side of current dc-link rectifier, the power transistors act like basic diode bridge rectifier. Free-wheeling diode is used to create a path for the current in the dc-link by proper control of the power transistors. Hence, minimum of one transistor from either the negative or positive side of the bridge remain switched-on. Unlike the voltage dc-link type converter, two bridge legs can be connected to the free-wheeling states. For this purpose, the state of just one switch is changed (Kuusela, Salo, & Tuusa, 2000).

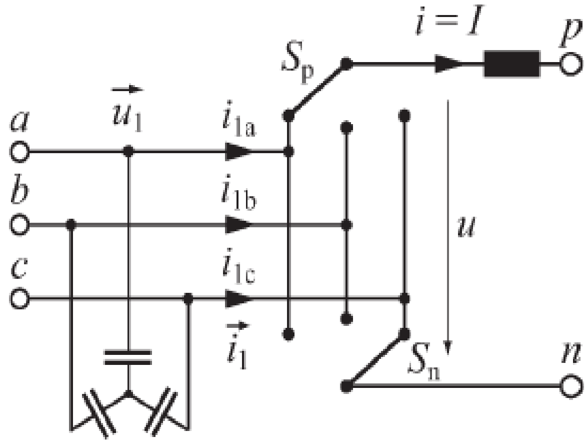
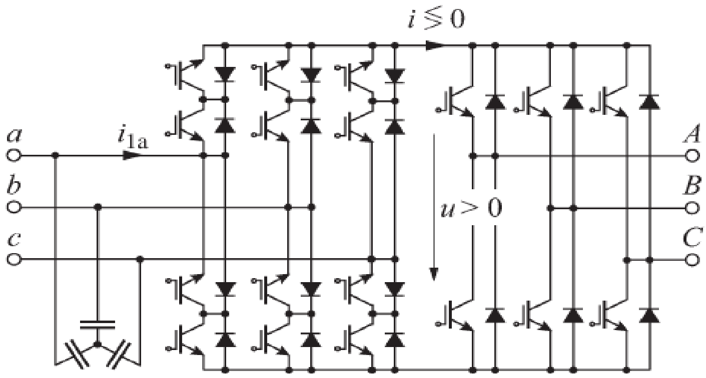


Figure 2.4: Current dc-link (Kuusela et al., 2000)

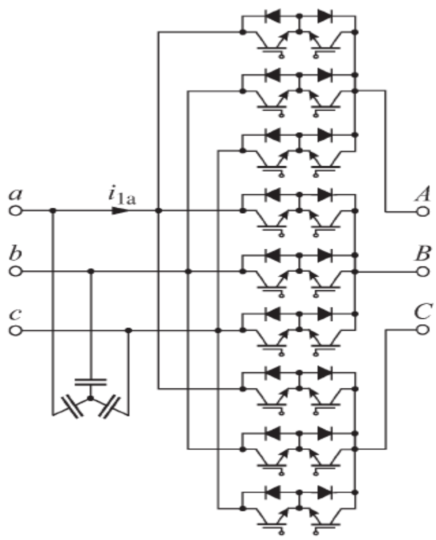
2.2.2 Matrix Converters

To improve the power density in $3-phase$ ac-ac converters, special converters known as "matrix converters (MC)" are introduced. These topologies work by producing a constant instantaneous-power using a $3-phase$ current-voltage system. The unique advantage of MC is that it directly converts ac-to-ac without the need of dc link which means there is improvement in the efficiency and reliability, since the losses and cost associated with the energy storing elements in the dc link are avoided. Presently IGBTs are often used as bidirectional switch in MC, because they can conduct current in both negative and positive direction while blocking voltage (Biswas, Jaiswal, & Agarwal, 2012; Ge et al., 2012; H. M. Hanafi, Hamzah, & Hamzah, 2009; Hakimas Mohd Hanafi, Hamzah, & Hamzah, 2009).

The direct MCs also called classical matrix converter (CMC) (Figure 2.5 (a)), achieve the conversion of current and voltage in just one stage. Moreover, alternative indirect conversion method is available using "indirect matrix converter (IMC)" shown in Figure 2.5 (b). independent stages are required for current and voltage conversions, just as in voltage-dc-link and current-dc-link converters, nevertheless no energy storing element is used. For the implementation of both IMC and CMC it required eighteen transistors (IGBTs) and eighteen diodes, in the fundamental structure, or twelve "RB-IGBTs" and six "RC-IGBTs" for indirect MC or eighteen "RB-IGBTs" for conventional MC. Therefore, the elimination of the energy storing device is paid with additional semiconductor devices (Mohapatra, Krushna K Mohan, 2006).



(a)



(b)

Figure 2.5: Basic three-phase ac–ac MC topologies (Mohapatra, Krushna K Mohan, 2006) (a) IMC (b) CMC

The fundamental matrix converters (IMC and CMC) voltage control-range is limited as compared to basic dc link converters (current-dc-link and voltage-dc-link), which is a serious disadvantage. To compensate this matrix converter topologies are combined with basic dc link converters to form a hybrid matrix converter. Nevertheless, energy storing components are required in HMC and there is high component-count compared to individual circuits. When the CMC is used in the hybrid matric converter it's called "Hybrid direct Matrix Converter (HDMC)" and it's referred as "Hybrid Indirect Matrix Converter (HIMC)" when IMC is used in the hybrid topology (Parikh & Parikh, 2012).

Figure 2.6 shows an example of HCMC “hybrid CMC” structure presented in (Erickson & Al-naseem, 2001). Four quadrant switches in the direct MC are substituted by series circuit with output-capacitors. Both step down and step up operations can be perform with this modified converter topology. In this topology, contrary to aforementioned topologies discussed, the output and input currents can be very well controlled, by employing minimum of five half bridge circuits. Furthermore, there is no need of external supply for the switching-cells.

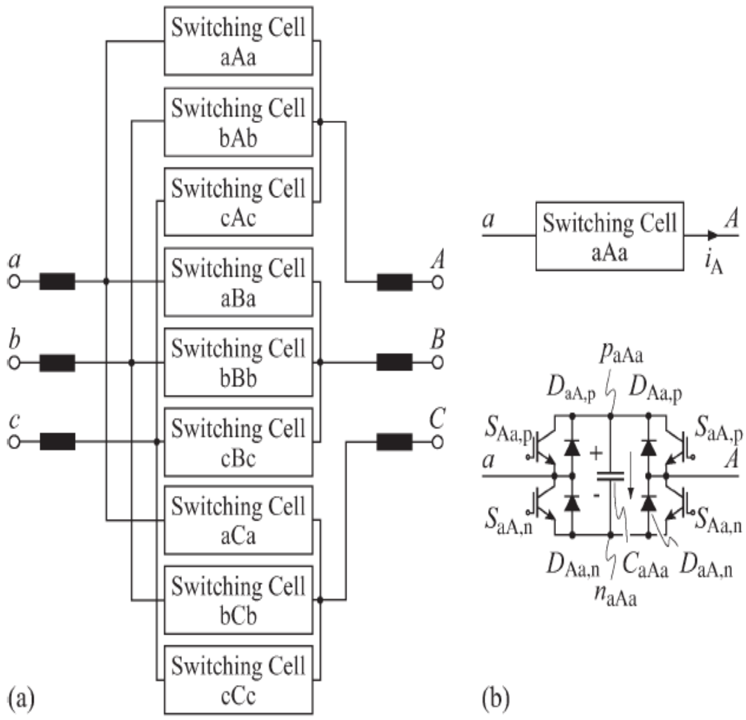


Figure 2.6: Hybrid matrix converters (a) Circuit topology (b) Switching cell (Erickson & Al-naseem, 2001)

Notwithstanding the numerous researches about matrix converters over decades, they are still scarce in market due to their technical complexity. This might also be related to high variation in the topologies, complicated modulation and dimension, compared to dc link converters. Matrix converters are considered by many researchers as realizable in future for several applications including mobile-utility power supply (Peng et al., 2003), wind-energy power systems (Peng et al., 2004), and bi-directional variable speed drive systems.

A comparison of the salient features of the fundamental three-phase ac-ac converter is presented in Table 2.1. four converter topologies are considered in the comparison; two dc-link and two matrix converter circuits (Kolar & Friedli, 2011).

Table 2.1: Comparison between basic ac-ac converter circuits

	Voltage dc-link	***Current dc-link***	***IMC***	***CMC***
No. of transistors	12	12	18	18
No. of diodes	12	12	18	18
No. of voltage sensors	4	6	3	3
No. of current sensors	4	3	2	2
PWM signal	12	12	12	18
Additional protection	No	yes	Yes	Yes

2.3 Z Source Inverter

The ZSI which was proposed in 2003 by (Fang Zheng Peng, 2003b) is a power electronic converter which is mostly applied in dc – ac power conversion; it has exciting characteristics such as single stage power inversion and the buck-boost properties. The ZSI is composed of four passive components of two capacitors and two inductors designed in X structure which constitutes the impedance structure or source. The impedance structure is placed in-between the source and the main converter body hence forming the impedance source inverter.

Figure 2.7, shows the basic ZSI topology which uses the shoot through state to increase the voltage gain or increase the magnitude of the source voltage; this advantage of the ZSI over other power electronic converters increases its scope of operation and reliability, produces single stage of power conversion (dc-ac), it has reduced cost, provides high efficiency, its size or volume is also reduced and has least component count. The application of ZSI in emerging energy sources such wind farms, photovoltaic systems, mini hydropower system and other current power electronic conversion systems such as hybrid and electric cars is propitious.

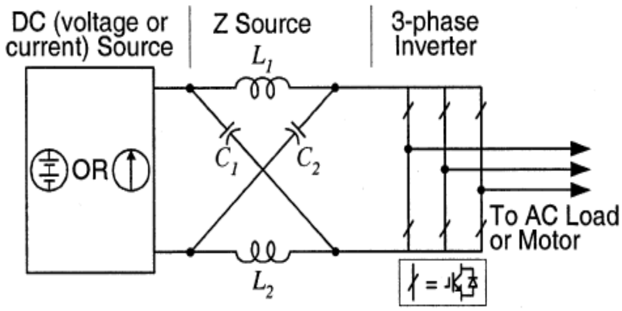


Figure 2.7: Basic ZSI structure (Ellabban & Abu-Rub, 2016)

The applications of ZSI is not limited to only dc-ac conversion but can also be applied to the following types of conversion; ac-dc, dc-dc, and ac-ac. Also, the impedance network of ZSI can be placed in any converter topology where the source is either VSI or CSI where the output of the converter has multilevel waveform functionality. There are several limitations of the conventional voltage source converter or current source converters such as; application of extra converter for buck-boost functions thereby increasing the cost of the system, volume of the system also increases considerably, efficiency is adversely affected because double stage conversion increases system losses. Turning on all switches on the same phase or leg will lead to short circuit or a condition called shoot-through which leads to destruction of the converter. The conventional VSI or CSI have poor immunity to electromagnetic interference (EMI) which is one of the major causes of unintentional gating of switches. Several topologies have been developed after the basic ZSI was presented in 2003 because of a number of drawbacks of the basic ZSI structure; there was very large inrush current during beginning of converter operation, the power flow was unidirectional due to the diode, suitable for semi heavy-load applications, the source current flow is discontinuous, higher capacitor voltage in impedance network, secluded source and inverter dc rail (Ellabban & Abu-Rub, 2016).

2.3.1 Δ-Sources Network

Several impedance network topologies have been published which seeks to improve or increase the voltage gain and also reduce the passive components in the impedance network. Answer to this is found in the coupled inductor application in Z source structures because they offer reduced cost and weight coupled with increased voltage gain at reduced component count. A new impedance network derived from the Y source structure, this topology is a novel (Δ-Source) one which provides least losses in the windings and also little magnetizing current hence productive application of the core material is gained resulting in reduced volume and weight. The cost of the Y source structure increases because of closed loop control is required to minimize the effects of leakage reactance (Hakemi, Sanatkar-Chayjani, & Monfared, 2017). The Δ-Source applies delta connection methodology in the connection of the three coupled inductors. Also, the adverse effects of leakage inductance are greatly minimized to improve the converter performance. The circuit of the proposed impedance network; Δ-Source network is shown in Figure 2.8. The shoot through and non-shoot through circuit are shown in Figure 2.9 a and b respectively.

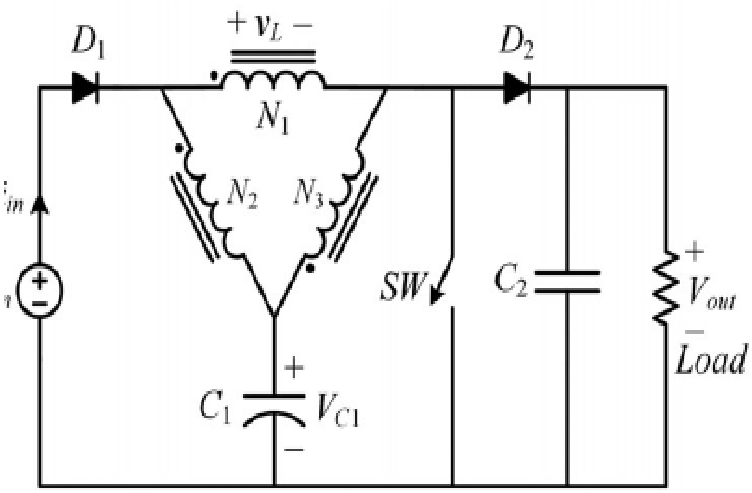


Figure 2.8: Δ-Source network (Hakemi et al., 2017)

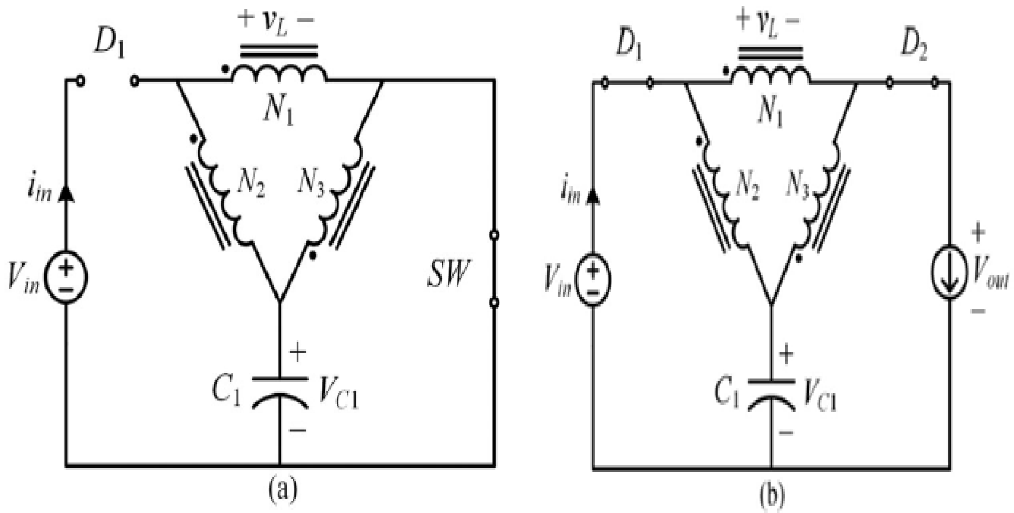


Figure 2.9: Δ-Source network a) Shoot through circuit b) Non-shoot through circuit (Hakemi et al., 2017)

2.3.2 Z-Source AC–AC Converter Topologies

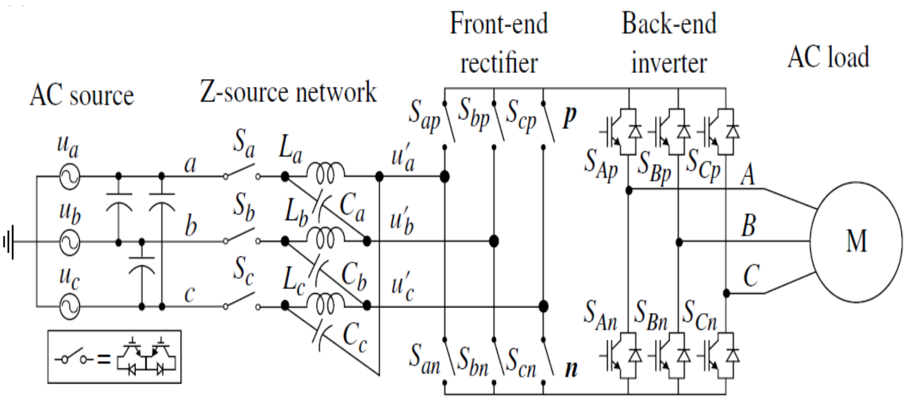
To solve the aforementioned problems related with the traditional ac/ac converters an impedance source power converter (Z-Source converter) is introduced in (Fang Zheng Peng, 2003b), after the introduction of the Z-source inverter (ZSI) various topologies have been introduced by modifying and utilization of this circuit. This include ac-to-dc, dc-to-ac, dc-to-dc and ac-to-ac, converter operations, as well as full-bridge and half-bridge conversions. In this section some of the famous Z-source based ac/ac converters are discussed.

2.3.2.1 Z-source Matrix Converters

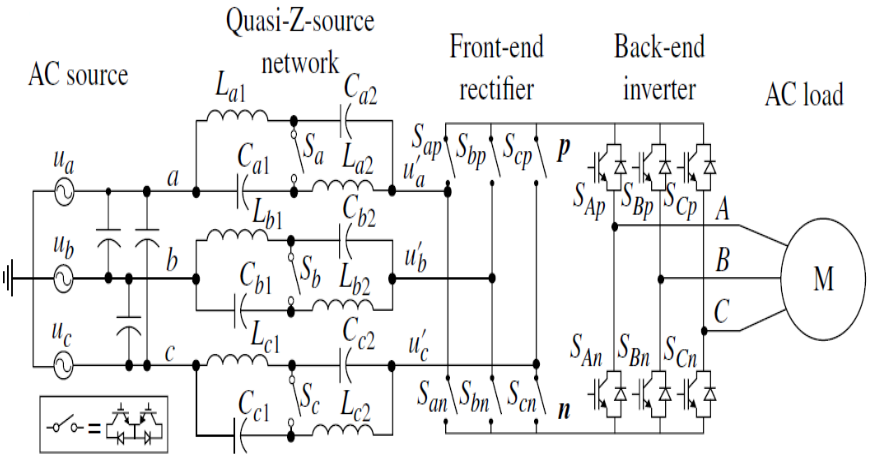
Combining the traditional matrix converters with a Z-network produces a Z-source based matrix converters. Since we have two structures of matrix converters; direct (CMC) and indirect (IMC), two Z-source based matrix converter topologies are produced. Z-source based IMC (ZIMC) and Z-source based CMC (ZCMC). Hence, the problem of voltage gain limitation in classical MC can be solved using this arrangement.

2.3.2.1.1 Z-source IMC (ZSIMC)

The recent converter topologies that combined Z-source with indirect matrix converters are proposed in (Liu, Ge, Jiang, Abu-Rub, & Peng, 2014; Shuo et al., 2010). Figure 2.10 shows how the converter circuit are used for ac/ac conversion system. They are composed of the following parts: A $3-phase$ alternating current source, a Z-source or quasi Z-source network, rectifier circuit, an inverter and alternating current load. The incorporation of the impedance network makes it possible for the converters to work in boost as well as buck modes (buck-boost).



(a)



(b)

Figure 2.10: ZSIMC Topologies (a) ZSIMC (Shuo et al., 2010) (b) qZSIMC (Liu et al., 2014)

Figure 2.10 (a) shows the Z-source based IMC structure which contain fewer components (three inductors and three capacitors) when compared with the quasi-Z-source IMC shown in Figure 2.10 (b) which has six capacitors and six inductors. Nevertheless, the voltage gains of the Z-source based IMC is limited to 1.15, and the q-Z-source IMC has an inherent phase-shift because of the Z-source network, and the control becomes inaccurate. Table 2.2, shows the comparison between these two topologies.

Table 2.2: Comparison between ZS-IMC and qZS-IMC

	ZSIMC	***qZSIMC***
Switching-voltage stress	Low	Low
Switching-current stress	Low	High
Voltage-gain	Low	High
Voltage-ripples	Low	High
Current-ripples	High	Low
L-stress	Low	High
C-stress	Middle	Low
Efficiency	High	Low

2.3.2.1.2 Z-source CMC (ZSCMC)

Another group of authors have combined Z-source with direct-matrix-converters (CMC) to produce Z-source based CMC known as "Z-source direct matrix converter (ZSCMC)". Similarly, with this arrangement voltage gain can be increase. Furthermore, the integration of impedance source makes commutation simpler in ZSCMC.

A class of $1-phase$ ac-ac converters that operates in both buck and boost mode is introduced in (Kaykhosravi et al., 2012). This topology is based on Z-source network and $1-phase$ matrix-converter (SPMC), an ac-ac buck/boost converter, this topology is shown in Figure 2.11. The converter topology (ZSSPMC) also has an advantage of buck/boost operation; to produce a step up voltage in-phase with input or a step down voltage out of phase with input.

In (X. Fang et al., 2010), a unique topology of Z-source network based MC is produced. This special topology is unique in the sense that it can be used to convert single phase source to a three phase for three phase load operation. This converter is referred as "single to three- phase Z- source matrix converter (ZSTZMC)", it is formed using Z-source network idea and theory of matrix conversion, Figure 2.12. The ZSSTMC topology can provide voltage of any amplitude and alleviate the limitation of voltage conversion ratio and unbalanced output-current.

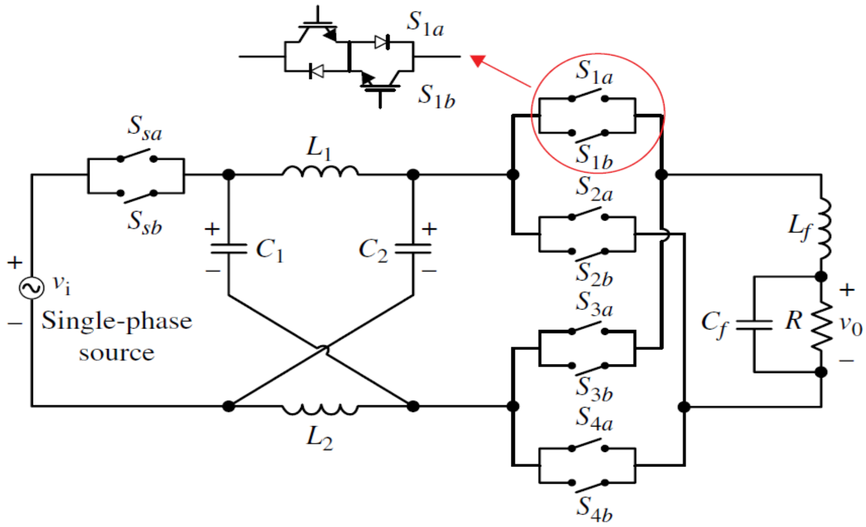


Figure 2.11: ZSSPMC (M.-K. Nguyen et al., 2009)

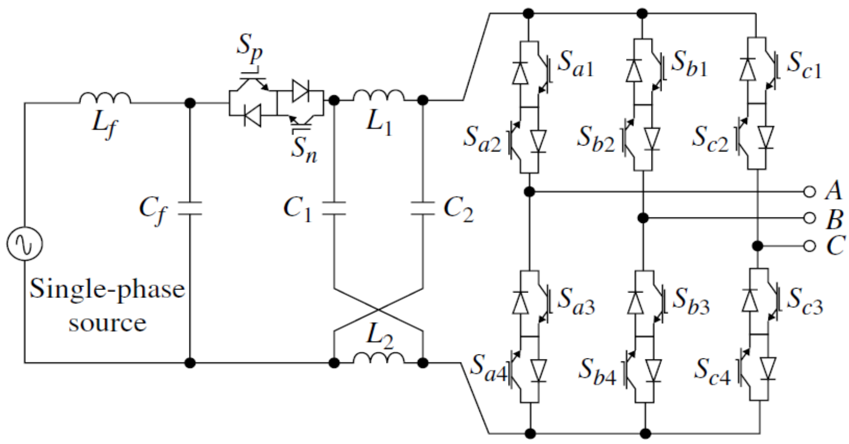


Figure 2.12: ZSSTMC (X. Fang et al., 2010)

Figure 2.13 (a) and (b) show the proposed single-phase Z-source, PWM voltage-fed, buck-boost converter and current-fed buck- boost converters, respectively. Both converters utilize only two active devices (S1 and S2), each combined with a full diode bridge for bidirectional voltage blocking and bidirectional cur- rent paths. All the inductors and capacitors are small and used to filter switching ripples.

The symmetrical Z-source network, which is a combination of two inductors and two capacitors, is the energy storage/filtering element for the Z-source ac–ac converter. Since the switching frequency is much higher than the ac source (or line) frequency, the inductor and capacitor requirements should be low. The proposed ac–ac converters can operate with PWM duty- ratio control in exactly the same way as for conventional dc-dc converters.

Figure 2.14 shows the switching functions common to both proposed ac-ac converters. As shown in Figure 2.14, S1 and S2 are turned on and off in complement. A small snubber circuit may be needed for each switch to suppress switching surges and to provide commutation paths. Table 2.3 shows the steady-state input-output voltage gains of these converters as a function of duty ratio D. By controlling the duty ratio, the output voltage can be regulated as desired.

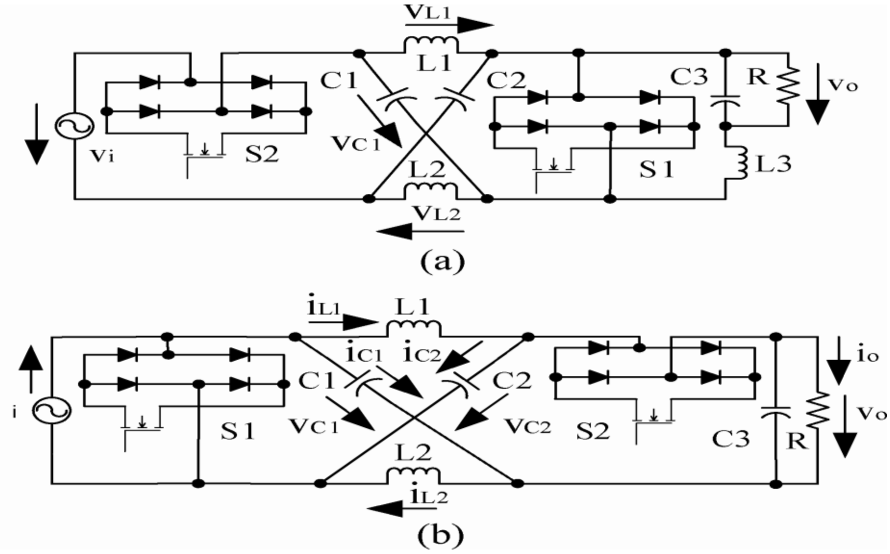


Figure 2.13: 1-phase Z-source ac–ac converter: (a) voltage-fed and (b) current-fed

Presented in (Tang et al., 2007; Banaei et al., 2016; Ahmed et al., 2016; Qian et al., 2011). This paper extends the Z-source concept to ac–ac conversion. Although the Z-source ac–ac converters given here are quite similar to those published in (Fang Zheng Peng, 2003b), some unique features revealed in this paper, such as phase reversing and buck-boosting are interesting for certain applications.

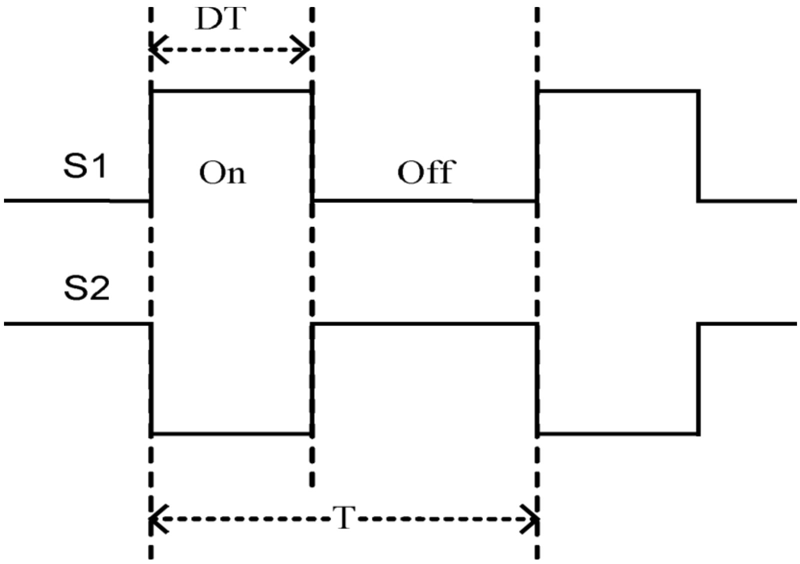


Figure 2.14: Duty-ratio control of Z-source ac–ac converters.

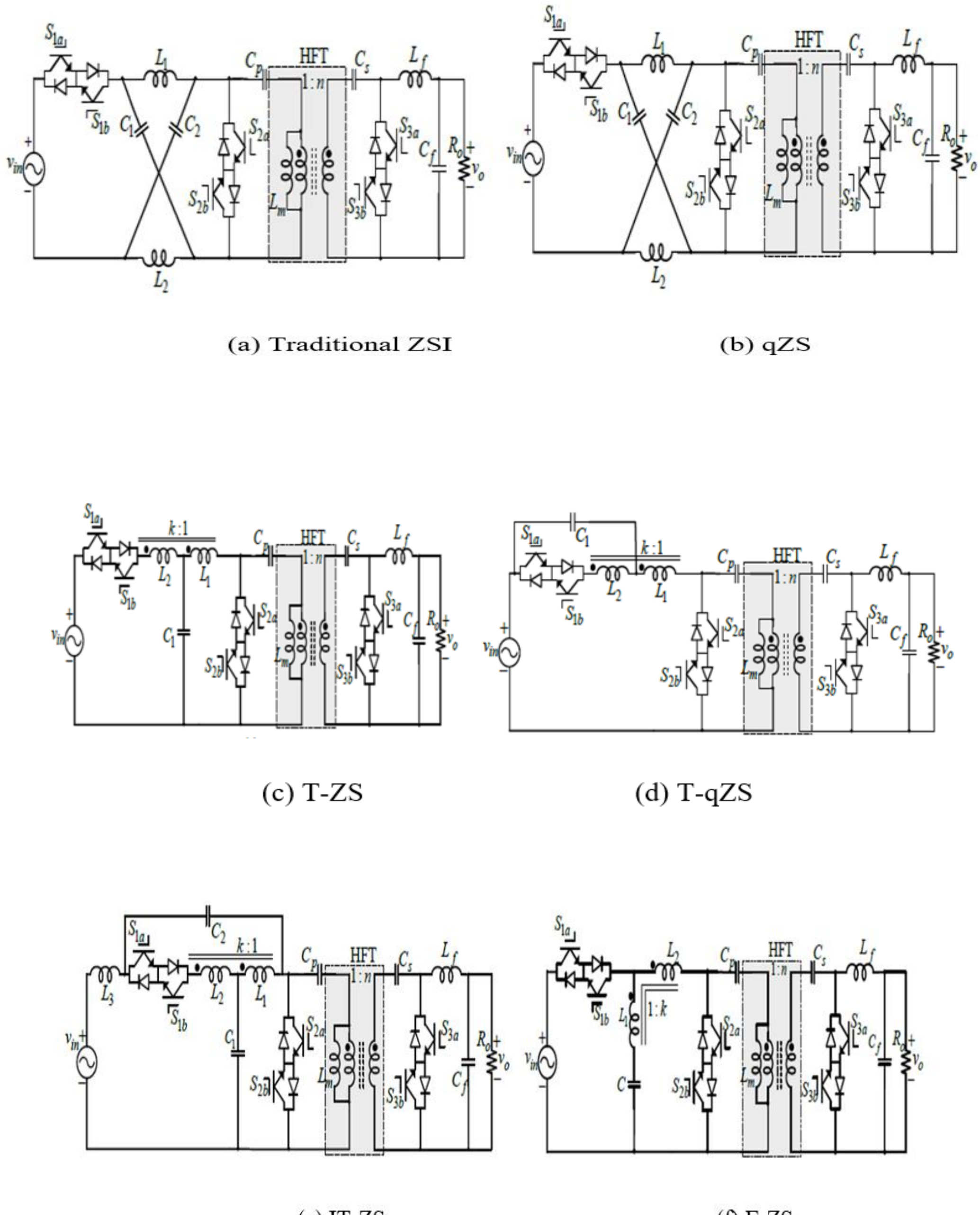
Table 2.3: Voltage transfer ratio of z-source ac–ac converters

Z-source ac-ac converter	Voltage Gain
Voltage-fed	$\frac{1-D}{1-2D}$
Current-fed	$\frac{1-2D}{1-D}$

In other to make any ZSI into ac-ac converter, bidirectional switches have to be used instead of the unidirectional switches and the H-bridge circuit replaced with bidirectional switches depending on the desired structure.

Examples of ac-ac ZSI converter topologies are qZSI, ZSI, Γ-ZSI (Banaei et al., 2016; X. P. Fang et al., 2005; Minh-Khai et al., 2010). Figure 2.15 shows the various ZSI topologies incorporated with HFTI structure. Any ZS topology where more diodes are required are suitable for convention into ac-ac ZS converter because substituting the diode with an active switch will maximize the losses in the system and also escalate the price of the structure. The following Z source converters are suitable for HFTI applications due to least passive and active switch count; Basic ZSI, qZSI, Γ-ZSI, TqZSI and ITZSI.

The different topologies shown Figure 2.15 are derived from the non-isolated converter types by adding the high frequency transformer isolation technology. The HFTI based converters have the same structural design with the difference the type of impedance network applied and the position of the impedance network (Cacciato, Consoli, Attanasio, & Gennaro, 2010). These components are same for each type of HFTI based converter; number of bidirectional switches, high frequency transformer, the output filter network (C_f and L_f), the primary and secondary blocking capacitors C_p and C_f respectively.



(a) Traditional ZSI (b) qZS

(c) T-ZS (d) T-qZS

(e) IT-ZS (f) Γ-ZS

Figure 2.15: HFTI ZS ac-ac converters (Ahmed & Cha, 2018)

The number of bidirectional switches in the entire HFTI based converters is equal i.e. to say that each converter has 3 bidirectional switches in each case made up of switches S_1 S_2 and S_3. Shows the ideal pulse width modulation scheme for these converters. Between the switching period $(1 – D)T$, switch S_1 is switched on whiles switches S_2 and S_3 are switched off, also during switching period DT, Switches S_2 and S_3 are switched on whiles S_1 is switched off, all this occurs during one cycle of the period T. In practical system, the switching between the switches (S_2 and S_3) does not occur concurrently because of the different properties of time delay (switching on and off time) for each switch. This drawback introduces dead time which cause the formation of current and voltage spikes that can destroy or damage the semiconductor switches. Smooth commutation of these switches requires the introduction of appropriate control strategy and snubber circuit. However, the snubber circuit introduced contains passive components; resistor and capacitor which adds extra cost to the system and minimizes the efficiency of the system.

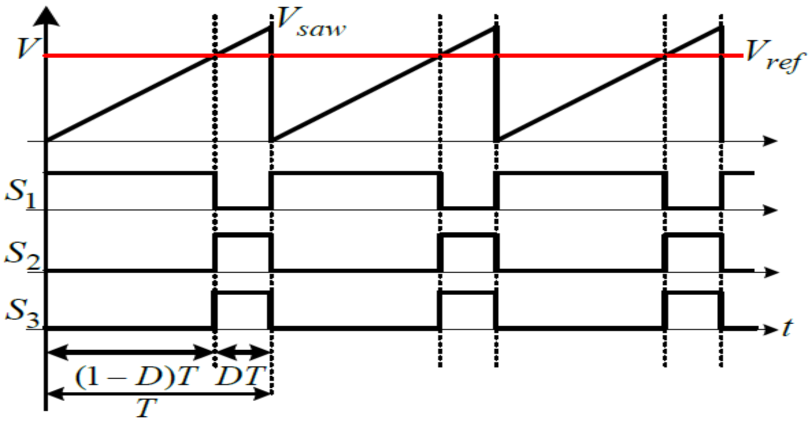


Figure 2.16: Pulse width modulation scheme HFTI converters (Ahmed & Cha, 2018)

2.4 AC-AC Converters as Dynamic voltage restorers

Dynamic voltage restoration refers to the process of compensating voltage swells and sags in electrical ac power distribution. Specially designed power electronic converters are installed between the source and the load to restore the line voltage to its desired value. Such converters are called dynamic voltage restorers (DVR).

With the increase in the utilization of electronic equipment and automations in the electricity utility system, production processes that are automated are getting more affected by disturbances from the power lines such as voltage swell and voltage sags. Such issues are the dominant effects against power quality in many industries. This development has made DVRs to get more popular in industries to minimize the influence of voltage swell/sag on the sensitive electronic loads. In fact a voltage sag for milliseconds can bring stop the entire production process, which will incur a lot of economic lost (B. H. Li et al., 2002; Newman et al., 2005).

Figure 2.17, depicted the structure of a typical DVR system to maintain normal operation. The voltage sag/swell is compensated by the DVR by either taking voltage or injecting voltage to the line in case of voltage swell and sag respectively. The voltages are injected into the system via the external series transformer. The external transformer functions to boost the voltage and provide electric isolation. This transformer is bulky, add cost and losses.

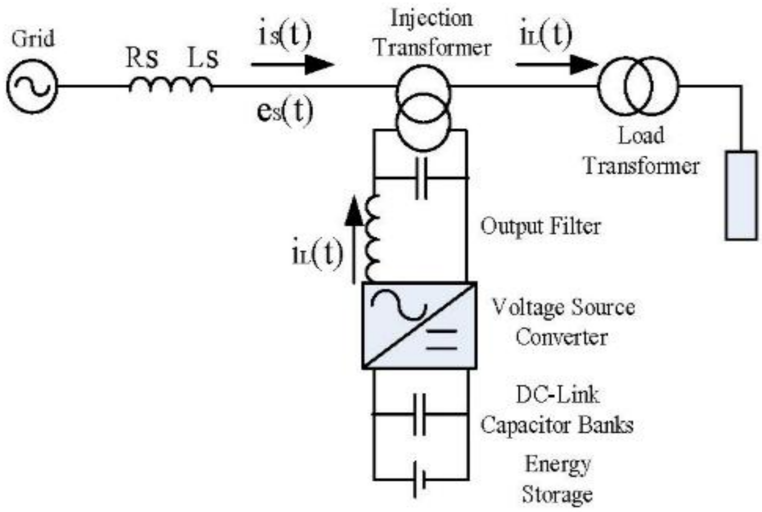


Figure 2.17: Typical dynamic restorer (DVR) (B. H. Li et al., 2002)

Auto-transformer based DVR is introduced to obtained a fast response at reduced cost. This topology incorporates a single PWM switch for each phase and eliminate the use of energy storage elements, which provide solution to the problem of high cost of voltage swell/sag compensation. The system is now cheaper and more reliable due to the reduction in the number of components. However, for effective performance this topology more subsystem must be designed (Lee et al., 2004).

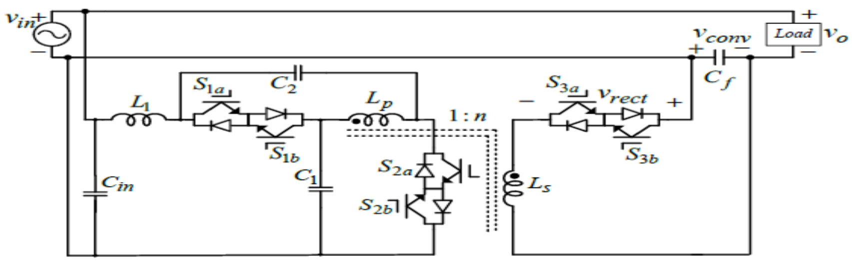
Following that another special topology of DVR system without external transformer is presented in (Vinnikov et al., 2014). This structure consists of decoupled energy storage elements and dc link, and series inverter/switches connection. The reliability and cost of this topology is almost equal to that of typical DVR. With increased stability, efficiency and reduced restorer losses. Nevertheless, in the event of single-phase sag, the capability of this topology is only 1/3 compared with typical DVR. In order to take care of this problem, the transformer less structure need to be extended.

Z-source based ac-ac converters are also used to realize DVR. PWM controlled Z-source is used combined with a transformer. Self-commutation technique is used to avoid the necessity of using snubber. The advantages of Z-source based $1-phase$ ac-ac converter include wide output voltage range, buck-boost capability, ability to minimize harmonic and inrush currents. These features make them suitable to be used in compensating both voltage swell and sag (Kaykhosravi et al., 2012; Minh-Khai et al., 2010; J. Rosas-Caro & Peng, 2009). However, the use of external transformers limits their application.

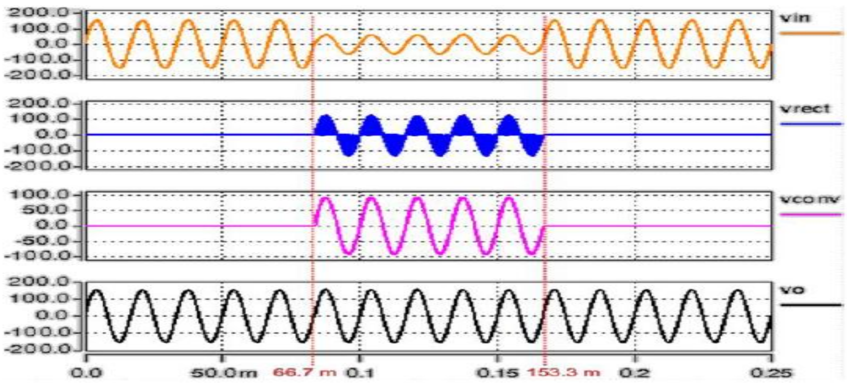
Despite the advantages and special characteristics exhibited by Z-network based single-phase ac-ac non-isolated converters, when used as dynamic voltage restorers (DVRs) (Kaykhosravi et al., 2012), an isolation between utility grid side and the output side (electronic load) is provided via an externally bulk line frequency transformer. Aforesaid frequency transformers have saturation problem and start-up inrush current, additionally, they are heavy and bulky resulting in increased cost and losses (B. H. Li et al., 2002; Newman et al., 2005; Wang et al., 2006). Moreover, voltage drop is resulted due to high impedance of this low-frequency transformers, and the voltage harmonics becomes serious alongside non-linear loads (Newman et al., 2005). In order to alleviate above shortcomings, HFT isolated (HFTI) Z-network based ac-ac converters are introduced (Ahmed et al., 2016). Such converter topology exterminates the necessity of externally line frequency transformer if adopted as DVR. Nevertheless, this converter uses additional bidirectional switch and extra passive components which increase their losses, volume, and cost.

Another topology is proposed in (Ahmed & Cha, 2018), this converter under study is introduced to subdue the above shortcomings of classical Z-source based ac-ac converters (X. P. Fang et al., 2005; Minh-Khai et al., 2010; M. K. Nguyen et al., 2012; Tang et al., 2007) as well as classical HFTI Z-source based ac-ac converter introduced in (Ahmed et al., 2016). It keeps the overall features of classical Z-source based ac-ac converters. It has HFT isolation and less passive component-count, HFT is incorporated for safety and electrical isolation. This is implying that an external line frequency transformer that is huge and expensive can be conserved for various uses like DVRs.

Figure. 2.18 shows an arrangement of a transmission line with a DVR scheme using the converter introduced in (Ahmed & Cha, 2018). In this topology, the line voltage v_{in} is connected in parallel with the converter input, and the converter output v_{conv}, the load, and line voltage are connected serially. Therein, in this form converter operates in three modes as explained underneath.



(a)



(b)

Figure 2.18: Application of the Z-source Converter as DVR (Ahmed & Cha, 2018)

CHAPTER 3

DESIGN, ANALYSIS AND SIMULATION RESULTS

3.1 Introduction

In this chapter analysis and simulation results for the single-phase HFT Z-source based ac-ac converter (Ahmed & Cha, 2018) are presented. The converter circuit description and development are explained in section 3.2. Followed by a comprehensive analysis of the converter in both boost and buck operation mode. Application of the converter as a dynamic voltage restorer (DVR) is also explored. To support the theory a simulation is conducted using PSCAD software and the result is reported.

3.2 Converter Circuit Description and Operation

Figure 3.1 shows the ac-ac single-phase HFTI ZS converter, produced by modifying the non-isolated ZS ac-ac converter presented in (Minh-Khai et al., 2010) and shown in Figure. 3.2. The new converter is obtained by replacement of the two inductors L_2 and L_f with high frequency transformer (HFT); reducing one magnetic core, and addition of a bidirectional switch S_3. Meanwhile, the number of passive components in both the isolated and the non-isolated converters are almost the same. This converter like the conventional non-isolated has a problem of commutation. Therefore soft-commutation technique is provided to eliminate voltage spikes for the switches without the use of snubber.

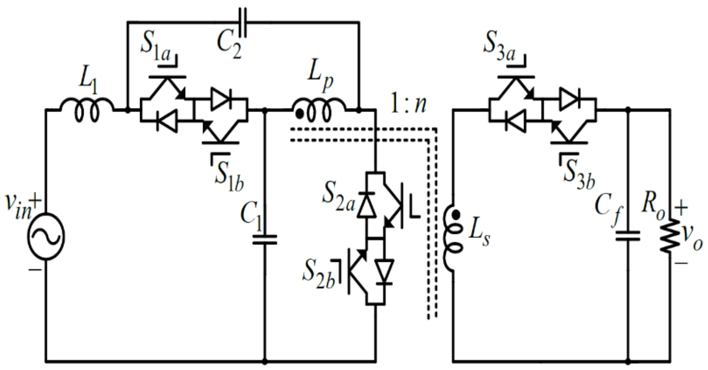


Figure 3.1: Ac-Ac Single-Phase HFT Isolated Z-Source Converter

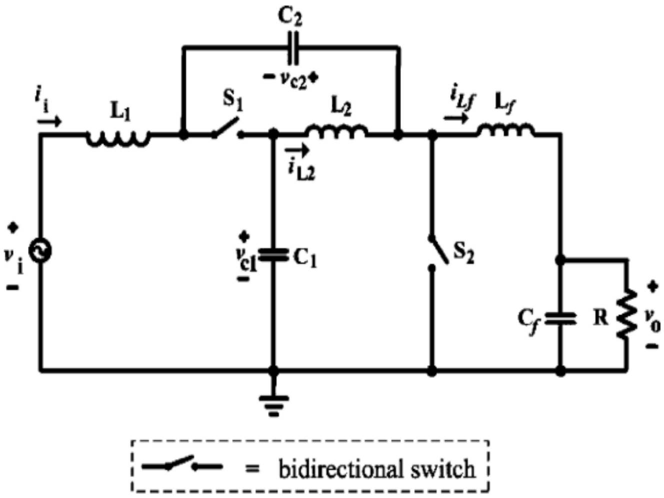


Figure 3.2: Single-phase Z-source ac–ac converter topology proposed in (Minh-Khai et al., 2010)

3.3 Boost Operational Mode

In Figure. 3.3 the gating pulses with safe-commutation technique and the key waveforms of the converter in boost operation mode are shown, for $n = 1$. When the input voltage v_{in} is positive, switches $S_{1a}, S_{2b}, and\ S_{3a},$ are turned-on throughout for safe-commutation reason. While $S_{2a},\ and\ S_{3b}$ are switched synchronously at high frequency, reciprocating switch S_{1b}. Figure. 3.4, 3.5 and 3.6 show the equivalent circuits of the converter in boost mode.

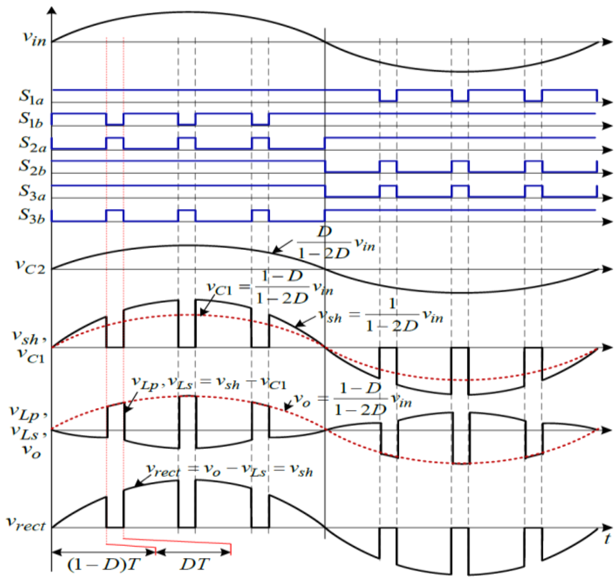


Figure 3.3: Boost mode key waveforms and switching pulses with soft commutation

Figure. 3.4 shows equivalent circuit of the converter in DT time interval, where switch S_{1b} is turned off, while switches S_{2a}, and S_{3b} are turned on, during this time interval, C_1 and C_2 discharge energy whereas inductor L_1 charges and store energy. Meanwhile, secondary side of the HFT charges the output capacitor C_f. Using KVL, the equations related to this interval are obtained as follows:

$$-v_{in} + v_{L1} - v_{C2} = 0 \tag{3.1}$$

$$-v_{C1} + v_{Lp} = 0 \tag{3.2}$$

$$-v_{Ls} + v_o = 0 \tag{3.3}$$

$$v_{sh} = v_{rect} = 0 \tag{3.4}$$

$$v_{Ls} = nv_{Lp} = v_o = nv_{C1} \tag{3.5}$$

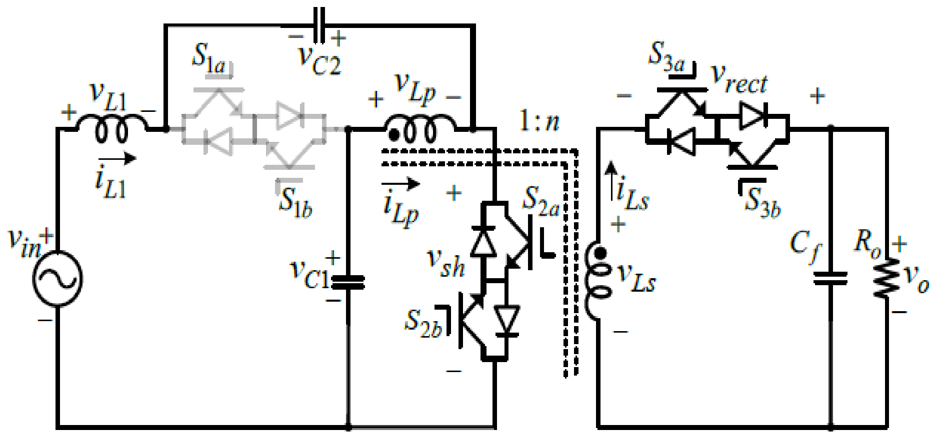
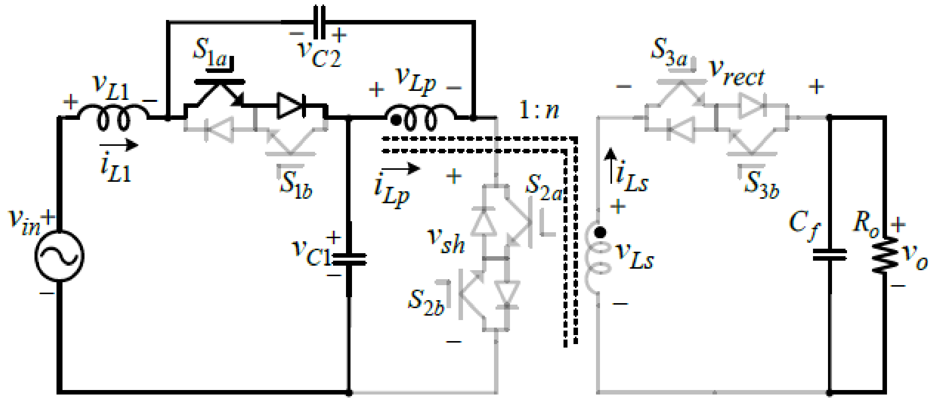


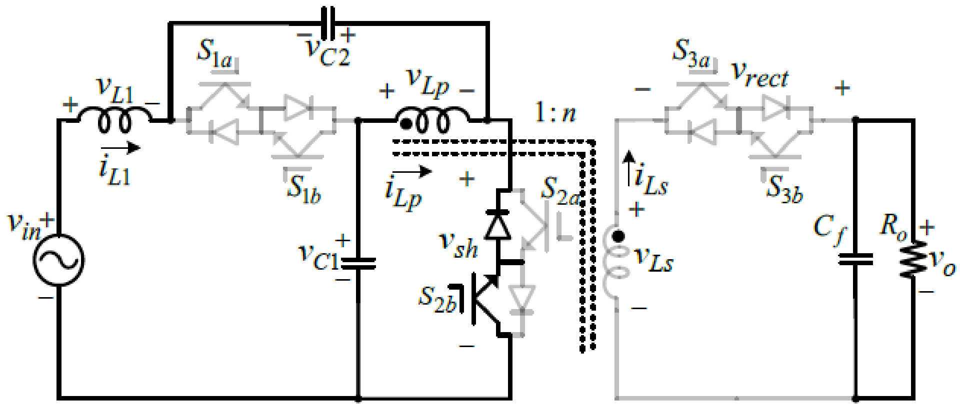
Figure 3.4: Boost mode equivalent circuit for DT interval

After the DT time interval, S_{2a} and S_{3b} switches are turned off, and the switch S_{1b}, is not yet turned on, as a result dead time occurs. As shown in Figure. 3.5 (a) and 3.5 (b), two modes of commutation can be implemented during this dead-time, the first mode as shown in Figure. 3.5 (a), takes place when the inductor currents i_{L1} and i_{Lp} are positive and then diodes of the switches S_{1b} and S_{1a} conduct. The second mode of commutation is shown in

Figure. 3.5 (b), which takes place when the inductor currents i_{L1} *and* i_{Lp} are negative. In this case, the diode of S_{2a} and switch S_{2b} conduct.



(a) Commutation mode I



(b) Commutation mode II

Figure 3.5: Boost mode equivalent circuit

The dead-time interval finished when S_{1b} switch is turned-on, and $(1-D)T$ time interval Figure. 3.6 starts, where S_{2a} and S_{3b} switches are turned off. Within this interval of time capacitors C_1 and C_2 are charged while L_1 discharges energy. Also, the output capacitor C_f discharges energy the load R_o. Similarly, applying KVL the following relationships are obtained:

$$-v_{in} + v_{L1} + v_{C1} = 0 \tag{3.6}$$

$$-v_{C2} - v_{Lp} = 0 \tag{3.7}$$

$$-v_{C1} - v_{C2} + v_{sh} = 0 \tag{3.8}$$

$$-v_{Ls} - v_{rect} + v_o = 0 \tag{3.9}$$

$$v_{Ls} = nv_{Lp} = v_o - v_{rect} = -nv_{C2} \tag{3.10}$$

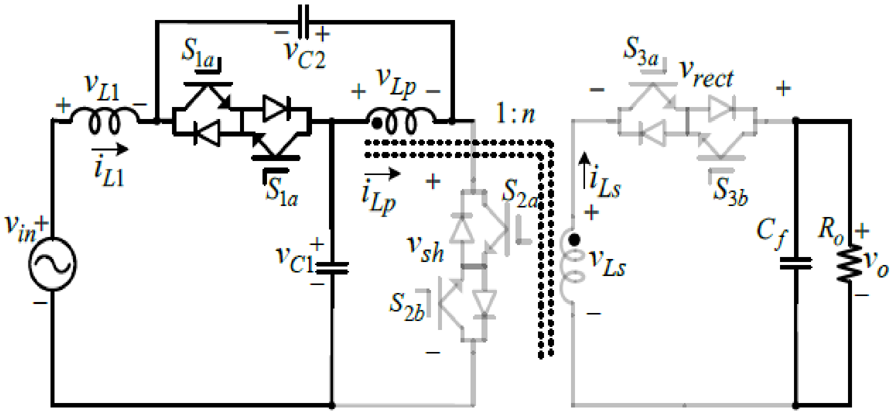


Figure 3.6: Boost mode equivalent circuit for (1-D)T interval

The capacitor voltages v_{C1} and v_{C2} can be obtained by using volt-second property of L_1 and L_P as

$$v_{C1} = \frac{1-D}{1-2D} v_{in} \tag{3.11}$$

$$v_{C2} = \frac{D}{1-2D} v_{in} \tag{3.12}$$

The expression for $v_{s\square}$ is obtained by using equations (3.11) and (3.12) in (3.8) i.e.

$$v_{s\square} = v_{C1} + v_{C2} = \frac{1-D}{1-2D} v_{in} + \frac{D}{1-2D} v_{in} = \frac{1}{1-2D} v_{in} \tag{3.13}$$

Similarly, by using equations (3.5), (3.11) and (3.12) in (3.10), we get

$$v_{rect} = (v_{C1} + v_{C2})n = \frac{1}{1-2D} nv_{in} \tag{3.14}$$

And

$$v_o = \frac{(1-D)}{1-2D} n v_{in} \tag{3.15}$$

Meanwhile, the voltage gain;

$$G = \frac{v_o}{v_{in}} = \frac{n(1-D)}{1-2D} \tag{3.16}$$

And the converter operates in boost mode for $0 < D < 0.5$.

3.3 Buck Operational Mode

In Figure. 3.7 the gating pulses with safe-commutation technique and the key waveforms of the converter in buck operation mode are shown. When the input voltage v_{in} is positive, switches $S_{1a}, S_{2b}, and\ S_{3b},$ are turned-on throughout for safe-commutation reason. While $S_{1b},\ and\ S_{3a}$ are switched on or off simultaneously, reciprocating switch $S_{2a},$ with little dead time in between. Figure. 3.8 and 3.9 show the equivalent circuits of the converter in buck mode.

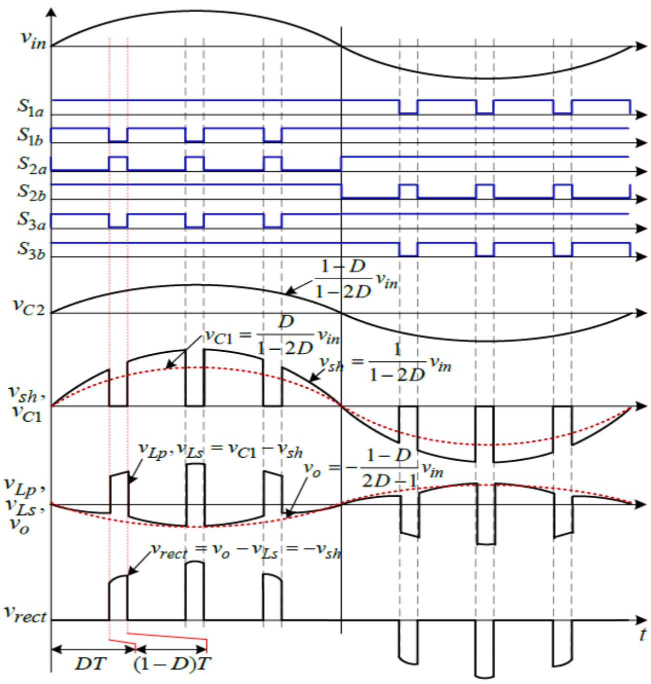


Figure 3.7: Buck mode key waveforms and switching pulses with safe commutation

Figure. 3.8 shows equivalent circuit of the converter in DT time interval, where switch S_{2a} is turned off, while switches S_{1b} *and* S_{3a} are turned on. During this time interval, inductor L_1 discharges energy whereas C_1 and C_2 charge. Meanwhile, secondary side of the HFT charges the output capacitor C_f. Using KVL, the equations related to this interval are obtained as follows:

$$-v_{in} + v_{L1} + v_{C1} = 0 \tag{3.17}$$

$$-v_{C2} - v_{Lp} = 0 \tag{3.18}$$

$$-v_{C1} - v_{C2} + v_{sh} = 0 \tag{3.19}$$

$$-v_{Ls} + v_o = 0 \tag{3.20}$$

$$v_{Ls} = nv_{Lp} = v_o = -nv_{C2} \tag{3.21}$$

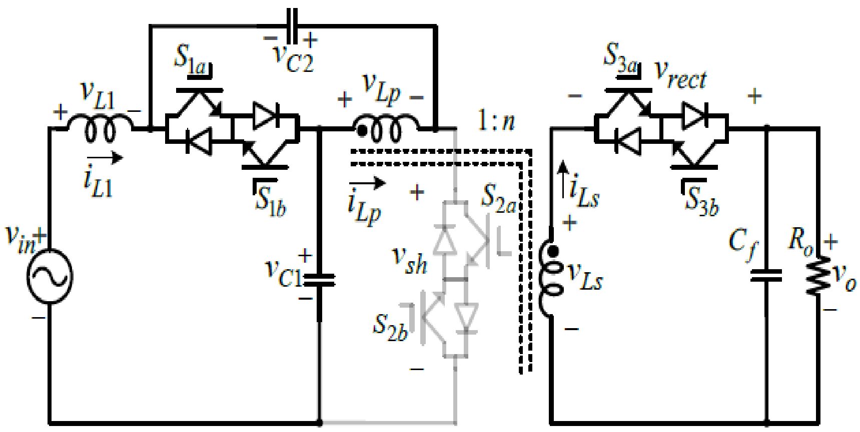


Figure 3.8: Buck mode equivalent circuit for DT interval

After the DT time interval, dead time occurs. Base on the direction of the inductor currents i_{L1} *and* i_{Lp} two modes of commutation maybe implemented during this dead-time as shown in Figure. 3.5 (a) and 3.5 (b).

As soon as the dead-time interval is finished, $(1 - D)T$ time interval Figure. 3.9 starts, where switch S_{2a} is switched-on while S_{1b} and S_{3a} switches are turned off. Therein, capacitors C_1 and C_2 discharged while inductor L_1 charges and store energy. Also, the output capacitor C_f discharges energy the load R_o. Similarly, applying KVL the following relationships are obtained:

$$-v_{in} + v_{L1} - v_{C2} = 0 \tag{3.22}$$

$$-v_{C1} + v_{Lp} = 0 \tag{3.23}$$

$$-v_{Ls} - v_{rect} + v_o = 0 \tag{3.24}$$

$$v_{Ls} = nv_{Lp} = v_o - v_{rect} = nv_{C1} \tag{3.25}$$

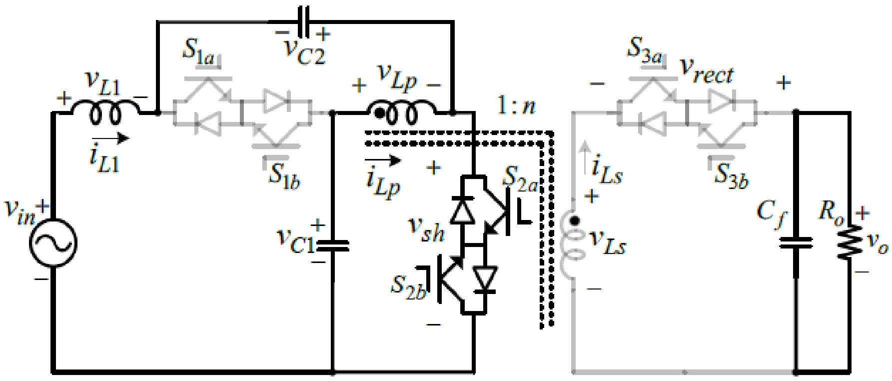


Figure 3.9: Buck mode equivalent circuit for (1-D)T interval(Ahmed & Cha, 2018)

The capacitor voltages v_{C1} and v_{C2} in this mode can also be obtained by using volt-second property of L_1 and L_P as

$$v_{C1} = \frac{D}{1-2D} v_{in} \tag{3.26}$$

$$v_{C2} = \frac{1-D}{1-2D} v_{in} \tag{3.27}$$

The expression for $v_{s\square}$ is obtained by using equations (3.26) and (3.27) in (3.18) i.e.

$$v_{s\square} = v_{C1} + v_{C2} = \frac{D}{1-2D} v_{in} + \frac{1-D}{1-2D} v_{in} = \frac{1}{1-2D} v_{in} \tag{3.28}$$

Similarly, by using equations (3.21), (3.24)-(3.26), v_{rect} and v_o are obtained as

$$v_o = -nv_{C2} = -\frac{(1-D)}{2D-1} nv_{in} \tag{3.29}$$

And

$$v_{rect} = v_o - nv_{C1} = -\frac{1}{2D-1}nv_{in} \tag{3.30}$$

Consequently, the voltage gain;

$$G = \frac{v_o}{v_{in}} = \frac{-n(1-D)}{2D-1} \tag{3.31}$$

And the converter operates in buck mode for $0.66 < D < 1$. The polarity of the output voltage in buck mode is reversed as indicated in (3.29) and (3.30). In Figure. 3.10 is shown the relationship between the voltage gain (G) and the duty ratio (D) for $n = 1$.

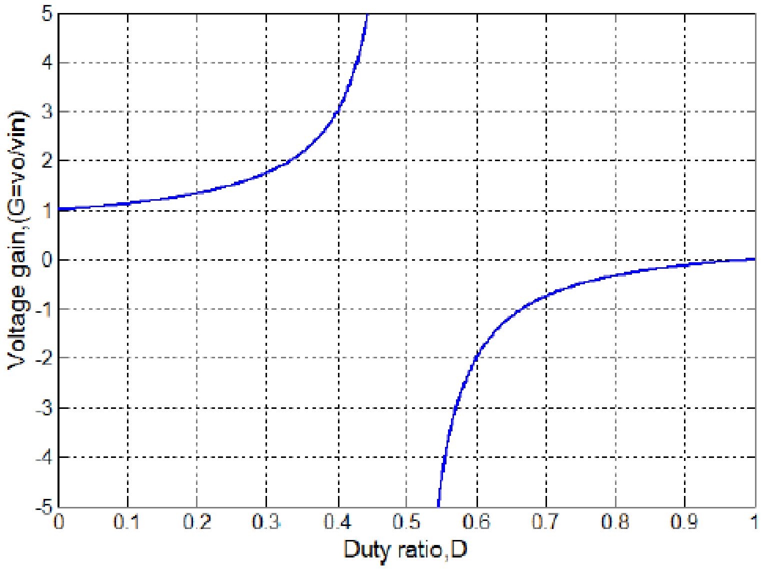


Figure 3.10: Plot of voltage gain against duty ratio (D) for n=1(Ahmed & Cha, 2018).

3.4 Application of the Converter as Dynamic Voltage Restorer (DVR)

Figure. 3.11 shows an arrangement of a transmission line with a DVR scheme using the converter discussed. In this topology, the line voltage v_{in} is connected in parallel with the converter input, and the converter output v_{conv}, is connected in series with the line voltage and the load. Therein, the converter operates in three modes as explained underneath.

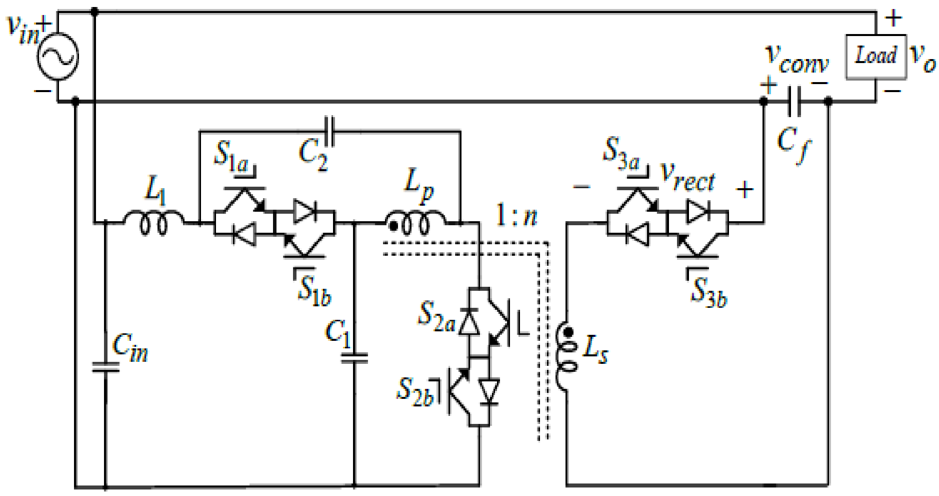


Figure 3.11: Application of the Converter as DVR

3.4.1 Mode 1: Bypass operation mode

The converter operates in a bypass mode when the line voltage is at its desired value (110 Vrms). Therein, the converter duty ratio $D = 1$, the switches S_{1a} and S_{1b} are fully switched-off, while $S_{2(a,b)}$ and $S_{3(a,b)}$ are fully switched-on. In this mode the load voltage v_o is equal to the line voltage v_{in}, since the output voltage of the converter is zero.

3.4.2 Mode 2: Boost operation mode

The converter operates in a boost mode when there is a voltage sag, i.e. the line voltage is lower than the desired value. Applying KVL to the circuit in Figure. 3.11

$$v_o = v_{in} + v_{conv} \tag{3.32}$$

Substituting for converter voltage in boost mode from equation (3.15) in to (3.32)

$$v_o = v_{in} + v_{in}\frac{1-D}{1-2D}, \quad 0 < D < 0.5 \tag{3.33}$$

It can be seen from (3.33) that the load voltage v_o is greater than the line voltage v_{in} and hence the sag can be compensated. Figure. 3.12 illustrate the condition when the converter is used to handle the voltage sag. When the line voltage drops to $44Vrms$, the converter operates in phase (boost) mode and therefore regulate the voltage to the desired value $110\ Vrms$.

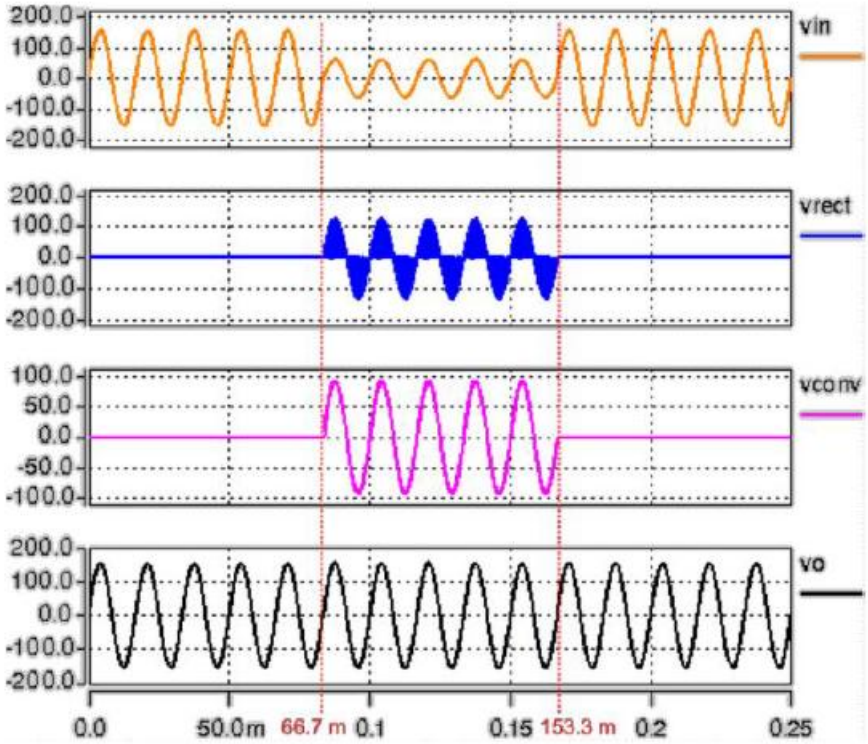


Figure 3.12: Simulation waveform for the DVR Boost operation for voltage sag compensation (Ahmed & Cha, 2018)

3.4.3 Mode 3: Buck operation mode

The converter operates in a buck mode when there is a voltage swell, i.e. the line voltage v_{in} is higher than the desired value. Applying KVL to the circuit in Figure. 3.11 and substituting for the converter voltage when it is operating in buck mode from (3.29)

$$v_o = v_{in} - v_{in}\frac{1-D}{2D-1}, \quad 0.66 < D < 1 \tag{3.34}$$

It can be seen from (3.34) that the load voltage v_o is less than the line voltage v_{in} and hence the swell can be compensated. Figure. 3.13 illustrate the condition when the converter is used to handle the voltage swell. When the line voltage increases from normal 110 Vrms to 165 Vrms, the converter operates out-of-phase (buck) mode and therefore regulate the voltage to the desired value 110 $Vrms$.

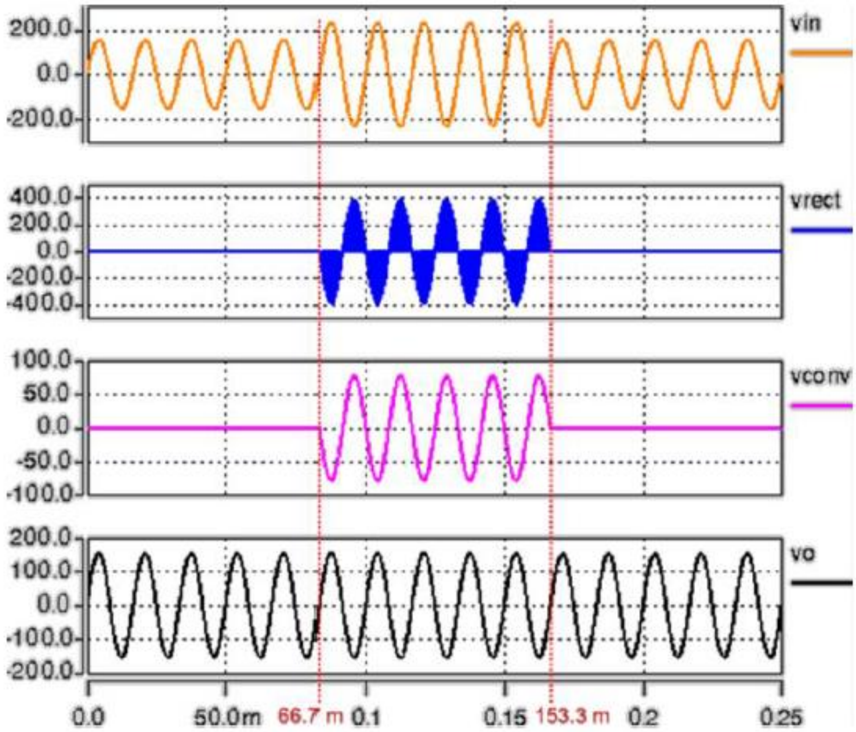


Figure 3.13: Simulation waveform for the DVR Buck operation for voltage swell operation

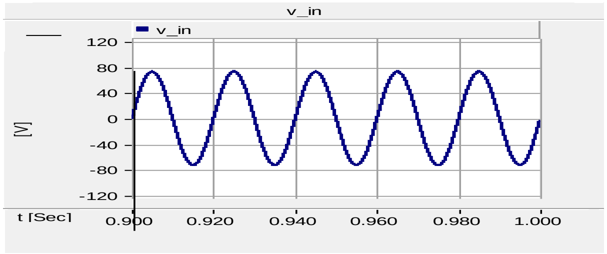
3.5 Simulation Results

For the purpose of validation, a simulation is conducted on the converter and the results are presented here. The simulation is carried out by using PSCAD / EMTDC-V4.2 software to confirm the theoretical analysis. The parameter specifications of the components used for the simulation are shown in table 3.1.

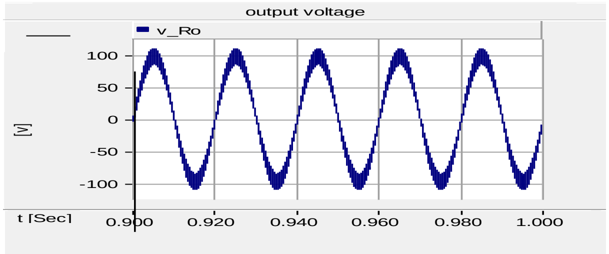
Table 3.1: Selected Parameters for Simulation

Input voltage (Boost operation)	$73V$
Input voltage (Buck operation)	$146V$
Switching frequency f_s	$20kHz$
Dead time for commutation	$0.5\ \mu s$
HFT	$Lm = 400\ \mu H, n = 1$
L_1	$800\ \mu H$
$C_1 = C_2 = C_o$	$6.8\ \mu F$
Duty ratio D (Boost operation)	0.25
Duty ratio D (Buck operation)	0.7
R_L	$60\ \Omega$

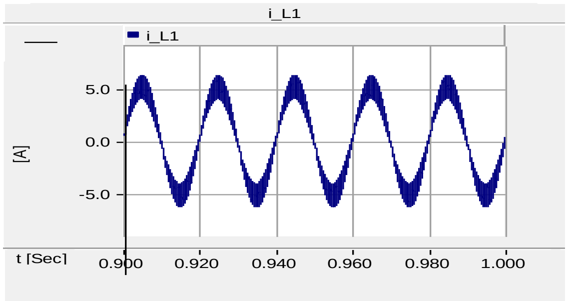
Figure. 3.14 and 3.15 show the simulation results for the converter during boost and buck operational modes respectively. Figure. 3.14 (a) shows the input voltage chosen to be $73\ V$, and Figure. 3.14 (b) shows the resulting output voltage from the converter, from the figure it can be seen that the output voltage is in-phase with the input voltage as expected and the peak value is approximately equal to $110\ V$ which almost the same as $109.5\ V$ calculated using equation (3.15). Similarly, Figure. 3.15 (a) shows the input voltage chosen to be $146\ V$, and Figure. 3.15 (b) shows the resulting output voltage, from the waveform it can also be observed that the output voltage is out-of-phase with the input voltage as expected from the theory and is equal to $-110\ V$ which is close to $-109.5\ V$ calculated using equation (3.29). Figure. 3.14 (c) and 3.15 (c) show the inductor currents for the boost and buck modes respectively.



(a)



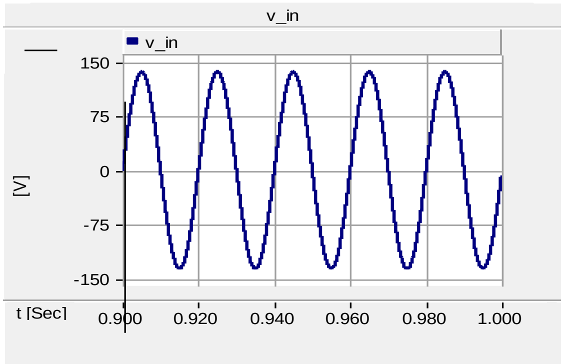
(b)



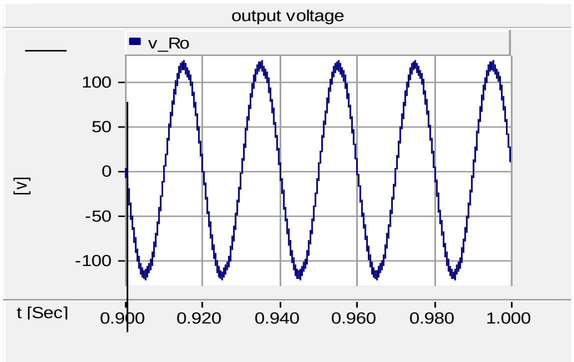
(c)

Figure 3.14: Simulation Results for boost mode

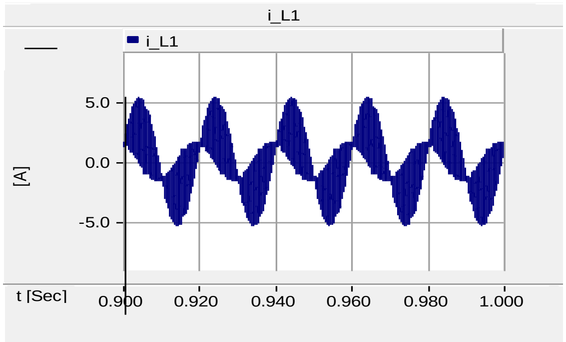
(a) input voltage v_{in} (b) output voltage v_o (c) inductor current i_{L1}



(a)



(b)



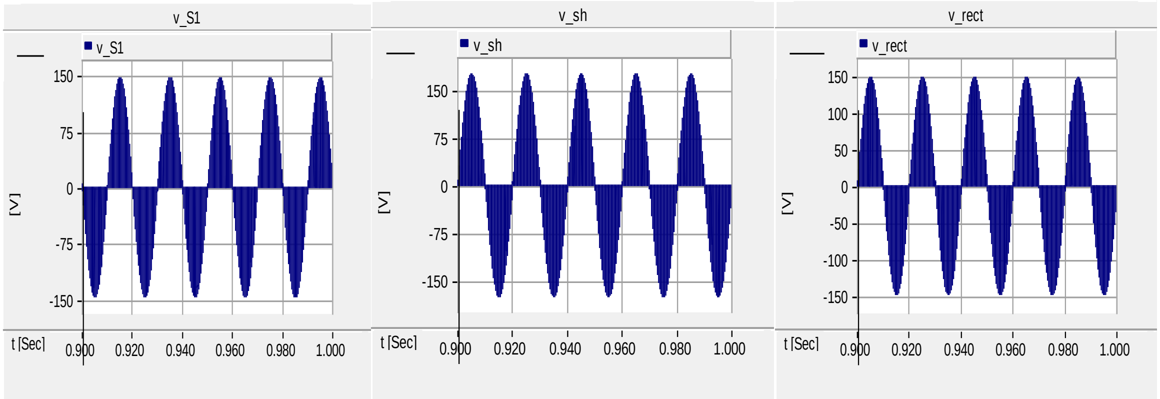
(c)

Figure 3.15: Simulation Results for buck mode

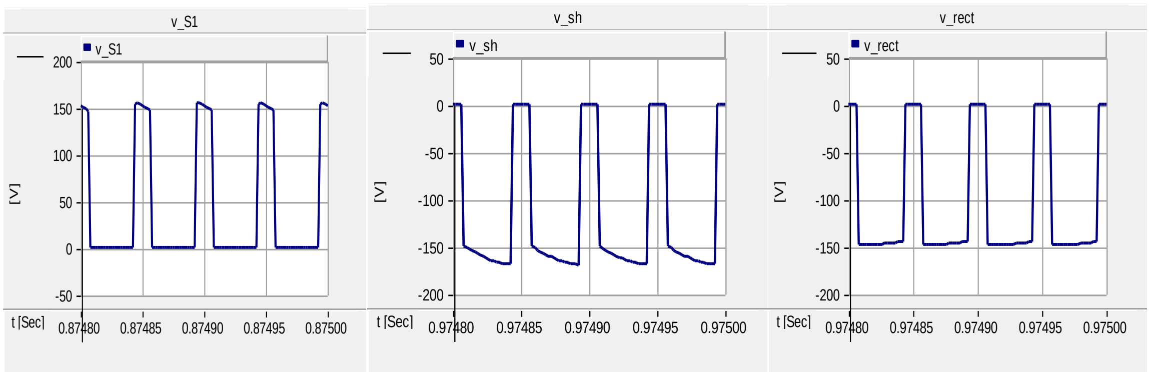
(a) input voltage v_{in} (b) output voltage v_o (c) inductor current i_{L1}

Figure. 3.16 shows the voltage stresses across the switches for the converter operating in boost mode, the simulated result for voltages v_{sh} and v_{react} is 146V which closed to the theoretical values of 146 V calculated using equations (3.13) and (3.14). Furthermore, in

Figure. 3.17, the waveforms of the capacitor voltages and also the voltage of the primary winding in the boost mode are shown.



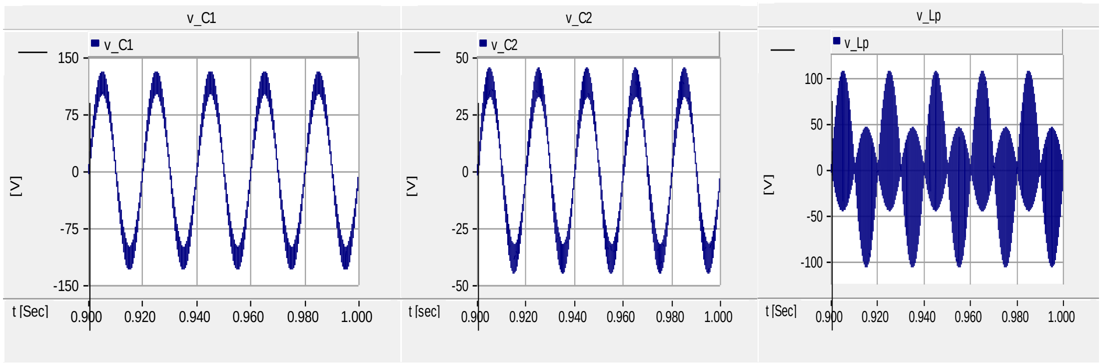
(a)



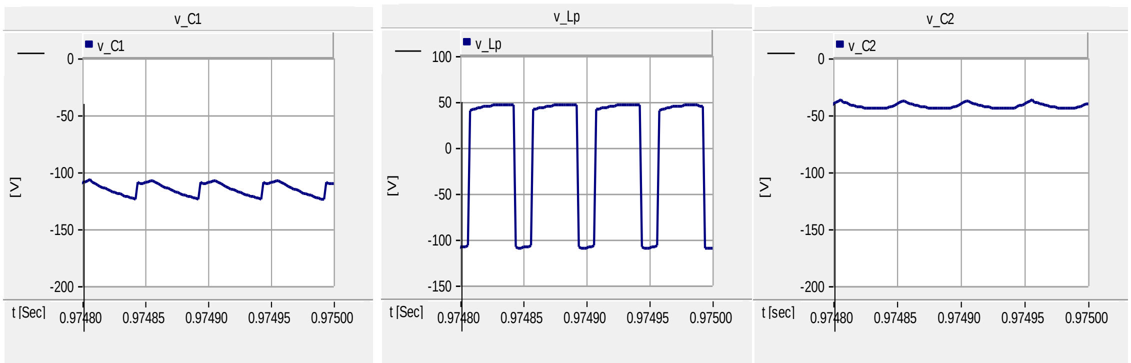
(b)

Figure 3.16: Simulation Results for boost operation mode

(a) voltage stresses across switches v_{s1b}, v_{S2a} and v_{S3b} (b) enlarged waveforms of (a)



(a)

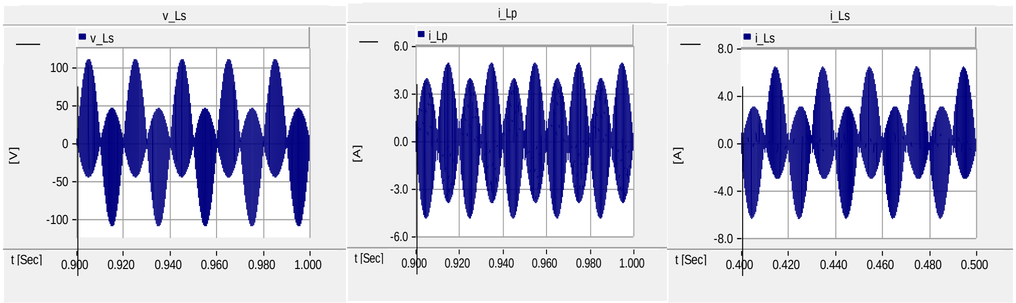


(b)

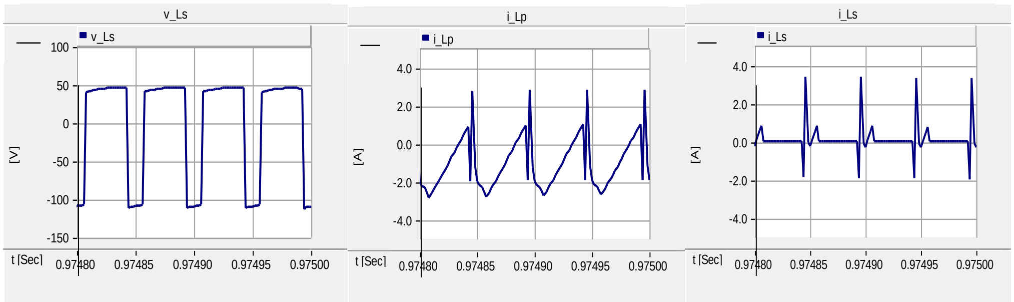
Figure 3.17: Simulation Results for boost operation mode

(a) capacitors and HFT primary voltages v_{C1}, v_{C2} and v_{Lp} (b) enlarged waveforms of (a)

The waveform of the secondary winding voltage L_s, and currents waveforms of the primary winding L_p and secondary winding voltage L_s of the HFT are shown in Figure. 3.18. meanwhile Figure. 3.19 shows the triggering pulses for the three bidirectional switches. In all the cases the simulation results are in consistent with the theoretical facts.



(a)



(b)

Figure 3.18: Simulation Results for boost operation mode

(a) HFT secondary voltage v_{Ls} currents i_{Lp} and i_{Ls} (b) enlarged waveforms of (a)

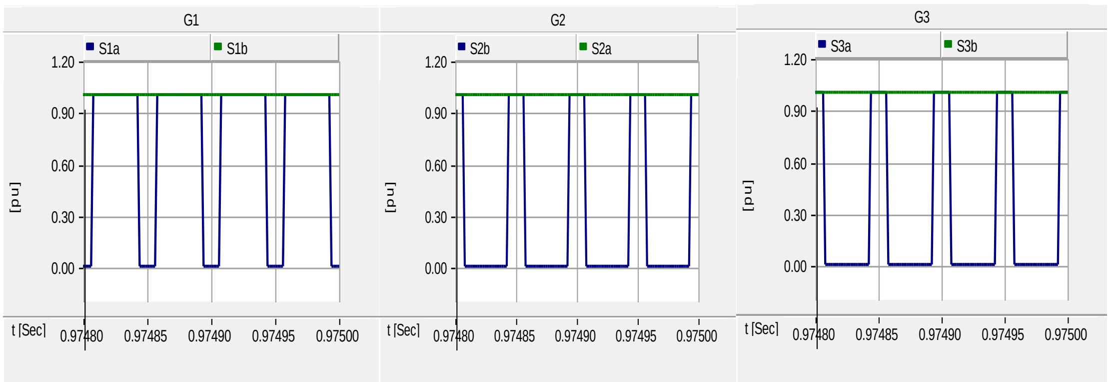


Figure 3.19: Triggering pulses for switches S_(1(a,b)), S_(2(a,b)) and S_(3(a,b))

3.6 Conclusion

In this chapter a detail analysis of the converter circuit has been presented. Two modes of operations were considered depending on the range of duty ratio; the converter operates in a boost mode when the duty ratio is $0 < D < 0.5$ and in a buck mode for $0.66 < D < 1$. In both cases the relevant relationships between various components voltages and currents have been established. An important application of the converter in as a DVR to handle voltage sag and swell has also been discussed. Finally, a simulation is conducted and the results are presented for purpose of supporting the theory. In all the cases when compared with the result obtained by calculating the voltages and currents using formulas the simulation result approximately equal the theoretical results. The few discrepancies might be a result of unavoidable errors.

CHAPTER 4

CONCLUSION AND FUTURE RECOMMENDATIONS

4.1 Conclusion

The thesis presents analysis and simulation of Z-network based ac-to-ac converter. Potential application of this converter as DVR (for dynamic voltage restoration) is also discussed. Simulation is conducted using PSCAD software to show the accuracy of the theoretical results.

This Z-source ac-ac converter, is built by adding isolation transformer to a basic ZS ac-ac converter, removing two inductor cores and addition of a single switch, hence, reducing one magnetic core. Moreover, soft-commutation strategy is used to eliminate the need for snubber circuit to handle voltage surges and spikes. Detailed analysis of converter for HFT turn ratio $n = 1$ is described by using suitable key waveforms and equivalent circuits. It operates as a buck and also as boost; boost mode take place when duty ratio ranges $0 < D < 0.5$ and buck take place when duty ratio is $0.66 < D < 1$. In both cases relevant relationships between various components voltages and currents have been established.

Dynamic voltage restoration refers to the process of compensating voltage swells and sags in electrical ac power distribution. Specially designed power electronic converters are installed between the source and the load to restore the line voltage to its desired value. Such converters are called dynamic voltage restorers (DVR). Application of the converter as a DVR to handle voltage sag and swell has also been thoroughly investigated. When used as a DVR it operates in three modes; first in a bypass mode when the line voltage is at its desired value, under this condition duty is $D = 1$, the converter output voltage is zero, therefore load voltage v_o and utility voltage v_{in} are equal. Secondly, in a boost mode when there is a voltage sag, i.e. the utility voltage is lower than the desired value, in this case the duty ratio is $0 < D < 0.5$. Finally, in a buck mode when there is a voltage swell, i.e. the utility voltage is higher than the desired value, in this case the duty ratio is $0.66 < D < 1$. In all the three modes appropriate waveforms are used.

Finally, for performance evaluation, a simulation is conducted on the converter and the results are reported and compared with the theoretical one. The simulation is carried out by using PSCAD / EMTDC-V4.2 software, the power systems computer-aided design (PSCAD) software has being widely used for simulations due to its accuracy, enhanced visualization and reliability. In all the cases when compared with the result obtained by calculating the voltages and currents using formulas the simulation results approximately equal the theoretical results. The few discrepancies are associated with inevitable errors.

Due to their many advantages including reduced harmonic current, high efficiency and high-power factor, dynamic voltage restoration is built using direct PWM based ac-ac converter, but these class of converters generally have problem of limited voltage gain. However, introduction of Z-network by Peng has provided a solution to the limited voltage gain and therefore a high output-voltage and buck-boost operation are possible.

By incorporating Z-networks a good number of 1-phase non isolated converter where designed with a number of advantages. However, despite the advantages and special characteristics exhibited when used as DVRs external huge line frequency transformer must be used to isolate the utility grid side and the output side. There is saturation problem in this frequency transformers, in addition they are heavy and bulky resulting in increased cost and losses. Moreover, there is voltage drop from this frequency transformer, which makes voltage harmonic high.

Z-source based ac-ac converter with HFT is introduced to handle these shortcomings, which exterminate the necessity of using external frequency transformer for applications when as a DVR. Nevertheless, existing converters in this category use additional bidirectional switch and extra passive components which increase their losses, volume, and cost.

The high frequency transformer (HFT) isolated 1-phase Z-source based ac-ac converter discussed in this thesis, solved all problems of non-isolated ac-ac converter and improved performance.

It retained almost all beneficial characteristics of non isolated Z-source ac-ac converters such as broad range of output voltage, improved reliability and ability to handle the harmonic and in-rush currents. Additionally, HFT is incorporated for safety and hence eliminate use of heavy frequency transformer, for dynamic voltage restoration applications. Compared to other isolated ZS converters it has less passive components; it saves two inductors and capacitors isolated Z-source based converters, thus, reducing the losses, weight and cost, thereby increasing efficiency and reliability.

4.2 Future Recommendations

The converter gain depends on the transformer turn ratio which means the can be adjusted by varying the turn ratio. In future an attempt will be made to find an optimal range for the turn ratio for practical voltage gains to make design easier. Furthermore, to handle the switching harmonics in the input it is recommended that an additional LC filter be incorporated to further reduce the ripples.

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